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The selection, instrumentation and calibration
of a low range pressure transducer for use in
Webb Institute Towing Tank experiments

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THE SELECTION, INSTRUMENTATION AND
CALIBRATION OF A LOW RANGE PRESSURE
TRANSDUCER FOR USE IN WEBB INSTITUTE
TOWING TANK EXPERIMENTS

RALPH M. SESLER
and
WALTER B. CHRISTMAS

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THE SELECTION, INSTRUMENTATION AND CALIBRATION
OF A LOW RANGE PRESSURE TRANSDUCER FOR USE
IN WEBB INSTITUTE TOWING TANK EXPERIMENTS

A THESIS SUBMITTED TO THE
FACULTY OF WEBB INSTITUTE OF NAVAL ARCHITECTURE
IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR A DEGREE OF MASTER OF SCIENCE
IN NAVAL ARCHITECTURE

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Thesis

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Abstract

A Schaevitz pressure transducer P476-A10 was selected for use with Webb Institute Towing Tank models in making pressure and velocity surveys. The instrumentation of this transducer included a 14 watt variable frequency power supply, a 1000 cycle filter, a cathode-ray oscilloscope, and a transducer output amplifier as an optional component.

By means of reading the amplitude change of the output wave forms on the cathode-ray oscilloscope it was possible to obtain pressure resolutions considerably better than .02 inches water.

The system containing this transducer should prove useful for conducting pressure and boundary layer surveys on four foot model hulls as well as for many other possible projects involving hydrodynamic studies.

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R. M. S.

W. B. C.

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Section I - Introduction

Background - The principles by which the results of ship model testing are expanded to the performance characteristics of a full size vessel were originated by William Froude in the late nineteenth Century. After many ensuing years of ship model testing, the art remains essentially an art and not yet fully a science. The fact that many successful predictions have been made for conventional hulls is principally the result of refinement in technique and the development through experience of various allowances and factors.

The expansion method used by model towing tank personnel in William Froude's time, as well as that of our own, assumes that the resistance of all bodies traveling in a fluid or fluids can be treated as if it were composed of two basic components, frictional and residual. With respect to the so-called frictional components of ship and model resistances, it is further assumed that the magnitude of frictional resistance of each hull is related in some manner to that of an "equivalent plank" of the same hull wetted surface area and "characteristic length" passing through the same fluids as the hull without causing waves or turbulence. All of the total resistance that does not appear in the equivalent plank friction resistance is

said to be residual (or better, non-frictional) resistance, the derived coefficient of which is regarded as common to both model and ship.

This expansion method when used with allowances and factors derived from experience has been found to give reasonably good predictions of full size ship effective horsepower requirements. It is, however, simply a procedure that was readily adaptable to the scientific instrumentation available during the late 1800's; the need for experience factors suggests the probability of poor predictions for unconventional hull designs.

The concept of the equivalent plank, though quite useful as a tool for making expansions, is neither intended nor is it expected to give exact values of frictional resistance. First of all, the profile of a plate towed through the water is very unlikely to be the same as that of a hull, so it would be quite difficult to ascertain without considerable accurate resistance test data for the shapes concerned what dimension could be regarded as truly characteristic. Finally, it should be noted that planks are essentially two dimensional shapes whereas ship and model hulls are definitely three dimensional shapes. At corresponding points along the lengths of these two wetted surfaces, there is a probability - almost a certainty - that there will be dissimilarities in the boundary layer or region within

which the fluid velocities are affected by boundary shear. This boundary shear, or viscous shear, presents itself in the form of frictional drag.

With the spectacular development of the scientific instrumentation and electronics industries, particularly within the past two decades, it should now be possible to obtain greater knowledge of component resistances with regard both to their mechanisms and to their true magnitudes. Increased understanding of the subject of vessel resistance, of course, reduces dependence upon allowances and experience factors and increases the likelihood of obtaining good predictions for the more unconventionally shaped vessels.

The component resistances (equivalent plank frictional resistance and residual resistance) chosen by Froude, though useful for making predictions, are not physically discrete nor are they amenable to detailed studies with respect to their mechanisms or magnitudes. Total hull resistance, however, may also be divided into that portion existing as pressure forces normal to and those forces tangential to the hull.¹ Pressures normal to the hull can be read at various points by means of a pressure measuring device and the readings integrated over the wetted surface to obtain hull resistance due to wavemaking and separation. Tangential forces, on the other hand, are a manifestation of the forementioned friction-producing boundary shear. While the fluid

velocities within a boundary layer may be either laminar or turbulent in nature, it should be possible to study the velocities (from free stream velocity at the edge of the boundary layer to a postulated zero velocity at the hull) by means of a Pitot tube, a pressure measuring device and Bernoulli's Theorem. The systematic series of normal pressure measurements and boundary layer velocity may be regarded, respectively, as pressure surveys and boundary layer surveys.

With regard to the practical application of these surveys, it should be noted that the results of a single survey need not be limited in use to the study of one resistance component. Take, for example, the case of a moving non-wavemaking submerged body. A knowledge of the total resistance of the submerged body and the results of a pressure survey will be useful for the following purposes:

1. In the absence of wavemaking or induced drag (assuming no lift), an integration of pressure measurements should give the magnitude of separation resistance.
2. A deduction of a computed magnitude of separation resistance from a measured total resistance can then be regarded as the magnitude of frictional resistance.
3. The region of separation can be studied with respect to its point of inception (or separation point) and to the frequency of sheddings.

In order to investigate the various components of total resistance, particularly with regard to that caused

by separation, it has been planned to make use of Webb Towing Tank models for pressure and possibly for velocity surveys. There are a number of means by which pressures can be read. On full size ships and on large models pressures are normally obtained by means of manometers and by electrical transducers of moderate sensitivity. Webb Towing Tank models, however, are quite small (about four feet long in contrast, for example, to the 20 foot models normally used at the David Taylor Model Basin) and the use of manometers or standing tubes is likely to be impractical for a number of reasons:

1. Previous experience with manometers has shown that a considerable amount of travel through the water may be required before a "settling down" of the liquid in the column is realized.² The Webb Towing Tank is quite short, about 93 feet overall including dock, and a requirement for repeated runs is almost a certainty.
2. In order to avoid surface tension errors, good practice dictates that the minimum inside diameter of a U-tube manometer be $\frac{1}{4}$ inch ($\frac{1}{2}$ inch for standpipes).³ This sets a practical limit on the compactness of the installation unless one is willing to apply corrections for capillary action or surface tension.
3. As a manometer cannot be read while it is underway, it is not possible to obtain and study any pressure variations that may be encountered, particularly around the stern where separation occurs.
4. The tubing assembly may not be compatible with regard to shape and desired location with the physical shape of the void within the model.

Our apparent discarding of the idea of possibly using manometers, therefore, leads us to the objective of this thesis project.

Objective - At modest expense to Webb Institute, it was desired to select, instrument, and test a liquid pressure measuring device useful for making pressure and velocity surveys about the wetted surface of a Webb Towing Tank model. Included in this thesis project is the determination of requirements, an industry-wide study of available devices or systems, a study into the possibility of designing an installation to suit our objectives wherever theoretical design criteria are available, instrumentation of the device if necessary, and the installation of the device or system and testing with a pitot tube.

The preceding background discussion indicated that a sensitive pressure measuring device or system would be useful in studying both the separation and frictional resistances of a moving submerged vessel. Needless to say there are many other studies in which the desired device would be useful. Among these additional studies are

1. Wake surveys,
2. Kármán Vortex frequency studies about bodies of various shapes, and
3. Pitot tube studies, particularly with respect to the establishment of the most desirable location of the static openings.

Section II

Selection of the Transducer

In the previous section it was stated that we wished to obtain and instrument a very sensitive water pressure measuring device at modest expense to Webb Institute. It was presumed that the selected device would initially have to convert pressure to some electrical quantity for the following reasons:

1. It was anticipated that very high sensitivity would be required for a device used in the Webb Towing Tank models and it was likely that considerable amplification would be necessary.
2. The model with which the device was to be used would be moving and it was desired to be able to make precise readings of the results at a remote location.

Any device capable of converting energy or an energy state of one form into energy or energy state of a different form can be regarded as a transducer. In this thesis, the unmodified words transducer and instrument shall both be regarded as a device that exhibits a measureable electrical characteristic such as induced voltage, resistance or reactance for a given pressure input.

The complete assembly of a transducer, its power supply and instrumentation shall be regarded as the transducer system or system. The power supply provides a source of electric current on which the transducer may exhibit its resistance or reactance or by which the trans-

ducer can exhibit an induced output voltage. The unit or assembly that receives directly from the transducer an electrical output and measures the electrical characteristic (resistance, reactance or voltage) exhibited by the transducer is the instrumentation. Usually the final (and sometimes the only) unit of the instrumentation is the indicator which offers visual measurements.

After consideration of a large number of transducers, a system employing a Schaevitz Linear Variable Differential Transformer (LVDT) Transducer was finally selected for use in Webb Towing Tank experiments. The process of selecting a transducer from among the many commercially available was accomplished by the following:

1. The establishment of the requirements for a useful transducer system, and
2. A study of each transducer design and associated instrumentation and an evaluation of each system with respect to its ability to fulfill the established requirements.

There were a number of basic requirements, of course, which had to be considered in the selection of a pressure measuring device or system, regardless of the type.

Among these very basic considerations were the following:

1. The desired sensitivity,
2. The full scale pressure or range of pressures to be measured, and
3. The type of fluid the pressure of which was to be measured.

Sensitivity, of course, may be defined as the magnitude

of output change exhibited by a system or component for a given input change. Almost all transducer instrumentation assemblies can be constructed to provide some means whereby system sensitivity could be controlled by the operator within certain limits. An increase of sensitivity, however, is almost always accompanied by a reduction of the useful system operating range, the second of these three considerations. This is a truism which applies to almost all scientific instrumentation and it forces the operator to establish the compromise between sensitivity and operating range best suited to his situation. With regard to the type of fluid to be handled, all of the transducers considered were capable of working with the head of at least one non-corrosive liquid.

Closely associated with the concept of sensitivity is that of resolution or the magnitude of the smallest change of input that can be detected and measured accurately. Whenever this magnitude is exceeded by that of the apparent error⁴ of an indicator reading, however, this apparent error will be regarded in this thesis as the resolution of the system. A prime requirement of good resolution is good sensitivity, but good sensitivity does not always insure good resolution.

Possible limitations on resolution as envisioned by the authors were repeatability, hysteresis and step reso-

lution. Repeatability is the random difference expressed as a percentage of full scale between any single output at any specified input from the average of all outputs obtained from repeated tests for the same value of input. Any change of output after the input has undergone a full cycle or "loop" of any wave shape is hysteresis. Hysteresis is normally expressed as a percentage of twice the amplitude of the cycle, the mean value of input lying anywhere within the working range. A plot of output versus input showing small horizontal and vertical steps is characteristic of instruments having step resolution and in magnitude this limitation also expressed as a percentage of the full scale advertized by the manufacturer. Instruments having continuous calibration plots on the other hand are said to have stepless or infinite resolution.

The question of resolution was the most important consideration in the selection of a useful transducer. In his tests conducted with manometers on an eight foot model, Hogben claimed a resolution of plus or minus .005 inches water.⁵ His paper also presented tables of pressure changes at various points at speed-length ratios of .8 to 1.1. Eggert, on the other hand, did not state the resolution he obtained with the manometers used with his twenty foot models, but his papers presented contours of pressure changes at intervals of .1 inches water to .5 inches water.^{6,7} (Figure II-1 reproduces the contours

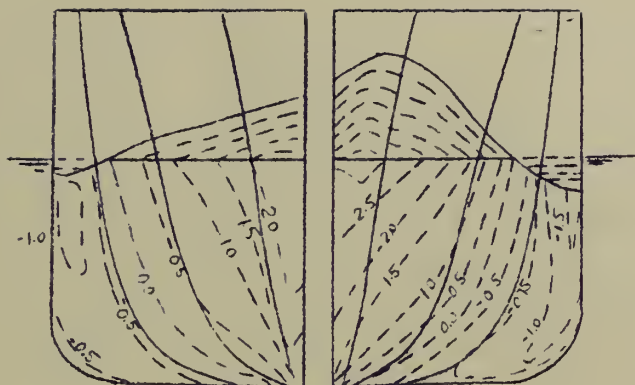


Fig.II-1. Contours of Change of Pressure, Model Length 20', speed 4 knots. (Reproduced from Eggert, E.F., "Form Resistance Experiments," Trans. SNAME, 1935, p 140, Fig.1)

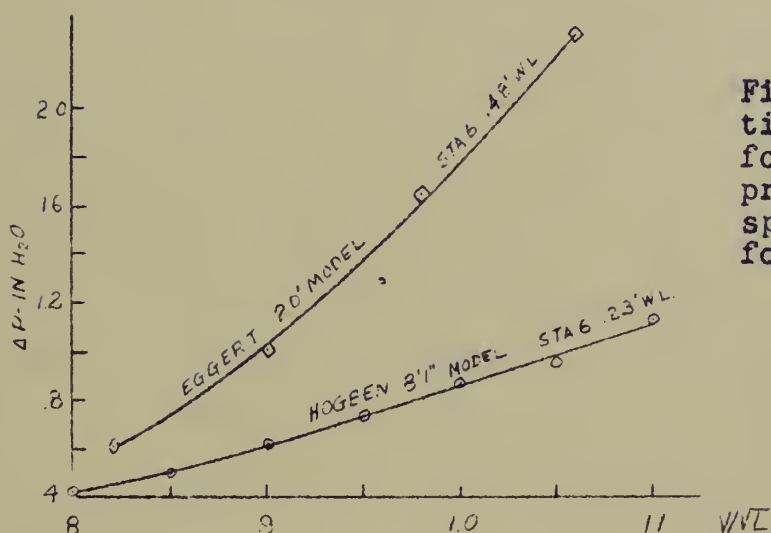


Fig.II-2. Reproduction of curves drawn for a comparison of pressure changes vs. speed-length ratio for two models.

Table II - 1

Comparison of Results - Pressure Surveys

	model length (L.W.L.)	Speed- Length Ratio	Maximum pressure changes (in.H ₂ O) Increase*	Decrease*
Eggert	20'	1.10	3.5	-1.3
		1.00	3.0	-1.0
Hogben	8'-1"	1.10	1.78	-.960
		1.00	1.50	-.720

*Maximums for Eggert model were interpolated between speed-length ratios of 1.12, 1.03 and .94.

of Eggert's twenty foot model proceeding at a speed-length ratio of .895.) Making use of plots such as that reproduced in Figure II-2 it was concluded that a desired interval between contours of .1 inches or at most .2 inches water should be adequate for the contours of a four foot model. Furthermore, it was decided that the plotting of contours of reasonable accuracy would require a pressure resolution of .03 inches water though .02 inches resolution would be highly preferred.

In view of the fact that resolution and operating range are interrelated quantities, a comparison of maximum pressure changes were also made and the results extrapolated to the four foot model. Table II-1 presents a comparison of the maximum pressure changes for these dissimilar models of different lengths at speed-length ratios of 1.00 and 1.10. For a four foot surface model underway at speed-length ratio of 1.00 it appeared that an operating range of one inch water increase and .5 inches water decrease would be sufficient in this one particular case. We were, of course, concerned only with orders of magnitude.

With regard to the prospect of having to use the system for boundary layer surveys, we made additional analyses concerning resolution and operating range. The head of a free stream velocity of .845 feet per second (corresponding to V/\sqrt{L} of .25) is

$$h = \frac{V^2}{6g} = .1866 V^2 = .1866 (8.45)^2 = .1332 \text{ in } H_2O$$

where V is fluid velocity (feet per second)
 h is velocity head (inches of fluid flowing) and
 g is gravitational acceleration, 32.15 feet per
 second squared.

An error of .03 inches representing the minimum resolution requirement we assigned to the transducer would have resulted in an indication of .1032 or .1632 inches water. The former figure represented a velocity of .744 feet per second or an error of

$$(.845 - .744) / .845 = 12\%$$

free stream velocity. The latter figure represented a velocity of .935 feet per second or an error of

$$(.935 - .845) / .845 = 11\%$$

free stream velocity. In view of the fact that velocities in a velocity survey would be extrapolated to zero at the hull, a velocity resolution of twelve percent free stream velocity was regarded as quite adequate. Most model velocity surveys, however, would be conducted at higher speed-length ratios than .25 and similar calculations for higher model speeds revealed considerable improvements in velocity resolution at the increased speeds.

The required operating range of the instrument itself was, of course, determined by the head of the highest free stream velocity expected. At a V/\bar{L} of 2.00 for the four foot model (corresponding to a speed of 6.756

feet per second) the free stream velocity head was 8.53 inches, well within the operating range of all but a few of the transducers studied. Again, the adjustment of instrumentation settings for an increase of sensitivity and improvement of resolution, however, might reduce the system operating range to exclude a part of the full extent of an expected pressure change. Further discussion of this matter is best delayed until the questions of instrumentation and indicators have been discussed.

In order that the most suitable transducer and associated instrumentation be obtained for our desired pressure measuring system, a number of aspects in addition to resolution and operating range had to be considered. With regard to the transducer and to its instrumentation we considered linearity, ability to follow low frequency pressure variations, ability to measure liquid pressure differences, dependability and ruggedness of the transducer, simplicity and dependability of instrumentation, and finally the question of costs.

Linearity, the first of these additional considerations, is the maximum diversion of a calibration curve from the "best-fit" straight line connection of the end points of a specified range. In evaluating this characteristic, the maximum diversion is usually expressed as a percentage of the difference between the output magnitudes represented by the end points of the range, one

of which is usually the origin or no-load point.

The desirability of good linearity is quite evident. In view of the fact that any transducer system constructed for the Webb Tank would have to be calibrated prior to initial use (and possibly on various occasions thereafter), a knowledge that a transducer has good linear output characteristics would reduce considerably the work of calibration. Most transducers, however, have adequate linearity for our purposes.

While it was not anticipated that the desired system would be used for measuring high frequency pressure pulsations, it was decided that the desired system should be useful for the determination of Kármán vortex shedding frequencies, either from a cylinder or from the stern of a model. These very low frequency pressure variations one might want to record, so for our system it was concluded that faithfulness of reproduction for low frequencies is highly desirable. The magnitudes of these frequencies vary widely with the size and shape of object as well as the magnitude of free stream velocity, but it was decided that the system should be capable of following frequencies of eight cycles per second and below.⁸ It was unlikely that we would have encountered any transducer that lacked the response required to reproduce frequencies within this range of low frequencies, but there were several types of instrumentation, particularly those that involved manual

bridge matching, with which non-repetitive pressure variations could have been studied only with considerable difficulty. Unless the system under discussion is likely to use instrumentation limiting the ability of the system to follow or to study low frequency pressure variations, however, no further mention will be made of this matter.

Before proceeding, a few additional definitions might now be appropriate. In most transducers the conversion of a pressure change to a linear displacement is accomplished by means of a diaphragm. Three examples of diaphragms are flat plates, bellows, and pressure capsules. A pressure capsule consists of two circular plates or disks having concentric corrugations welded or soldered to each other around the circumference. A difference of pressures exerted upon the two surfaces of any diaphragm will be regarded as a net pressure.

Earlier in this thesis it was noted that system range is very likely to be restricted for the sake of desired increase of sensitivity and improvement of resolution. As the linear displacement of a diaphragm is always determined by the net pressure, it is still possible to have measured a pressure outside of a particular range by placing on the opposite side of the diaphragm or reverse face a known controlled pressure. Proper control of this backup or reference pressure could then bring the

net pressure back to some point within the operating range established by settings on the instrumentation. In some instances, moreover, this backup pressure may also be employed to provide compensation for a pressure or suction on the opposite surface of the diaphragm, or pressure face, that would have normally damaged the transducer. Those assemblies designed to provide a liquid reference pressure on the reverse face are regarded as liquid reference pressure systems, and likewise, those that exert a gas reference pressure are termed gas reference pressure systems.

It was learned by the authors through considerable practical experience that a liquid reference pressure system would be highly preferred to the gas reference system. From this it may be inferred that the transducer selected for the system should be capable of measuring the net pressure of two liquids. Figures II-3 and II-4 illustrate and the accompanying captions describe the operation of a sample design of each of these two reference systems. It is quite evident from a study of these figures that mishandling (which the authors found could happen frequently) of any reference pressure assembly could result in a liquid entering a region where it is not desired. For the transducer incapable of handling a liquid reference pressure medium, this region in which liquid is not desired would include the transducer it-

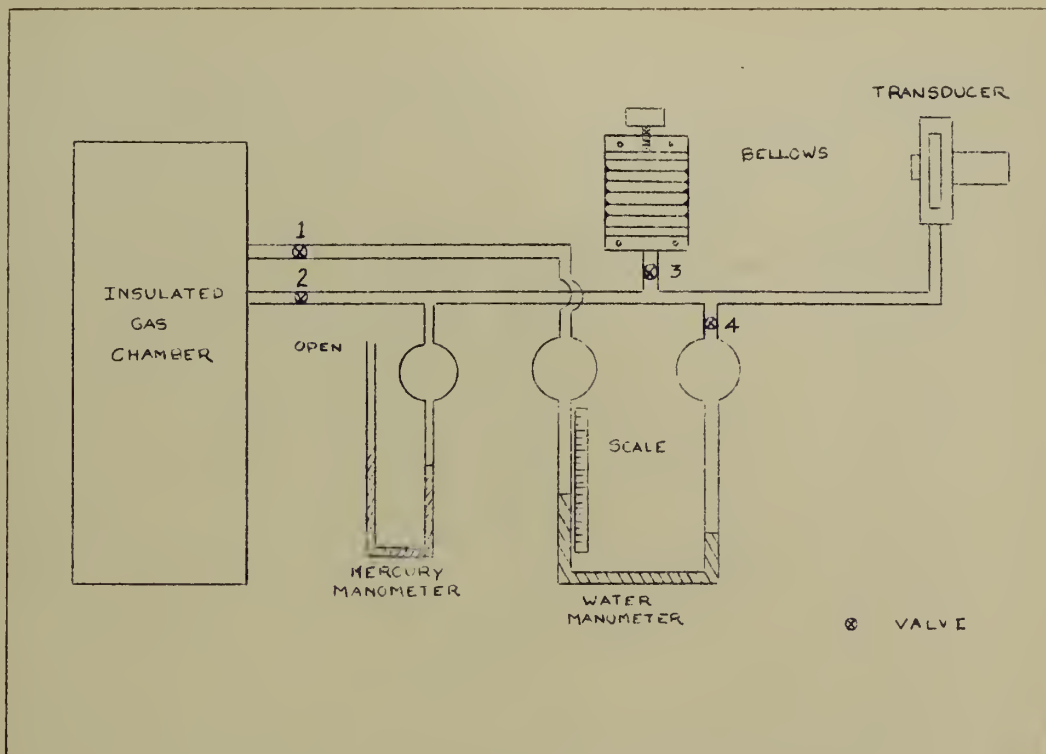


Figure II - 3. Gas Reference System
(Combined with a gas calibration system)

With valves 1, 3 and 4 closed and valve 2 open the system functions strictly as a gas reference pressure system. The insulated gas chamber volume is very large in comparison with the remaining gas-filled sections of the system; thus once filled with a gas (such as nitrogen, which is relatively inert) under a given pressure the system tends to remain at a constant pressure above or below atmospheric pressure. Pressure fluctuations in the uninsulated portions of this system, caused by ambient temperature changes, are damped out by the large volume of gas remaining at reasonably constant temperature.

With valve 2 closed and valves 1, 3 and 4 open the system acts as a gas calibration system. The bellows provides a pressure change, and the measurement of the change is accomplished through the use of a water manometer which can be slanted for greater accuracy.

The mercury manometer is used in both the reference and calibration system only if the pressure acting on the pressure face of the transducer pressure element is subject to atmospheric pressure changes.

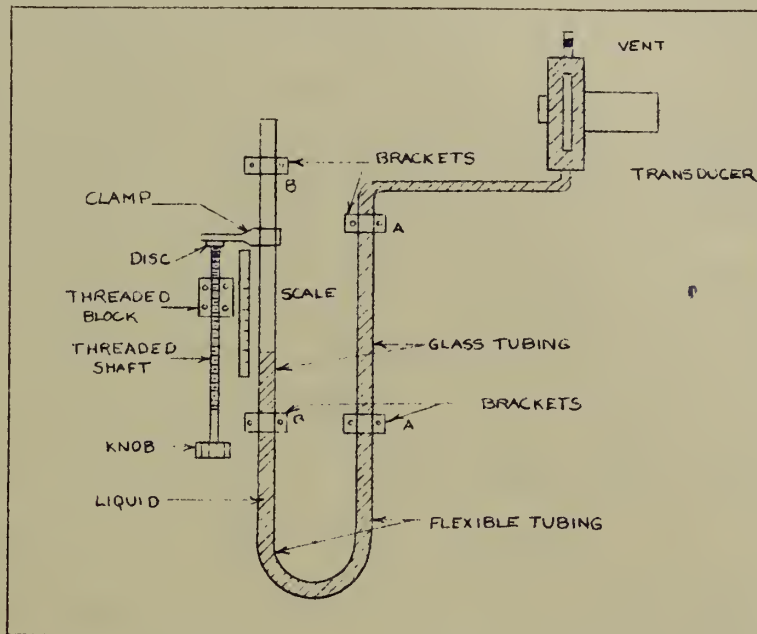


Figure II - 4 Liquid Reference System
(Combined with a liquid calibration system)

In the construction of such a system brackets A are a tight fit, and brackets B permit a sliding fit. The clamp is secured firmly to the glass tube. The threaded block is mounted on the same backing as the brackets A and B.

As the knob is turned, the shaft is advanced through the block forcing the clamp and the left glass tubing up or down. In this manner the height of liquid in the left tubing is controlled and can be measured by the rule. The difference between the height of water in the left tube and the center line of the transducer is the magnitude of the backup pressure. The above arrangement, of course, is suitable for a negative backup pressure. It can be made positive, however, by locating the transducer below the level of liquid in the left tubing.

self thus increasing the likelihood of damage to the transducer. Provisions may be made in the apparatus to reduce or eliminate this possible hazard by the use of reservoirs, drains, or water traps, or by avoiding the use of a liquid in the assembly. Allowing this liquid to drain or to collect in a reservoir, however, might effect the release of a backup pressure intended to prevent possible damage to the diaphragm on account of excessive pressure or suction on the pressure face. Reference systems, on the other hand, that use no liquid are difficult to control and monitor.⁹

With regard to dependability and ruggedness, a good knowledge of basic construction details assisted us in making reasonable comparisons between designs. Among transducers of the same and different designs there were some additional criteria useful in helping to make an intelligent comparison:

1. Many of these instruments were apparently intended for use in missiles and the specifications frequently indicated the number of accelerations of gravity the instrument could withstand without damage.

2. Some manufacturers, usually through subsequent correspondence, indicated the maximum pressure the diaphragm could be expected to withstand without damage.

A note of caution with respect to these criteria should be exercised. Among instruments of the same basic design there tended to be a wide range of figures regarding max-



imum acceleration and pressure before damage while there appeared to be considerably less diversity among the average of these figures offered for each of the different designs. It certainly appeared, therefore, that manufacturers tended to apply their own criteria, particularly with regard to factors of safety, in computing these specifications that primarily concerned ruggedness.

While a detailed study of transducer instrumentation is likely to be very lengthy - well over half of our efforts on this project were spent in studying or working with instrumentation - the establishment of requirements was quite easy. It was desired that the instrumentation be basically simple and dependable; but it should also be stable (i.e., it should give steady visual indications for a constant transducer output), easy to operate and maintain, and inexpensive to procure.

Past discussions have indicated that sensitivity (hence resolution) is controlled at the instrumentation assembly and that operating range is affected by this sensitivity setting. It is convenient to express this relationship as a ratio of useful operating range to the resolution or simply the range-resolution ratio. With the exception of those instrumentation assemblies which require manual matching in a bridge of a transducer output impedance, this ratio will be determined solely by the capabilities of the indicator. The values of the im-



pedances in the arms of the manually operated impedance bridge assembly, on the other hand, controls the range-resolution ratio for the system; it is probably the only type of instrumentation, therefore, that has a direct effect on this ratio.

Little needs to be said concerning the question of system costs. While we wanted to economise, we still desired that the transducer be useful for the anticipated pressure and boundary layer surveys and for as many other projects as possible.

In addition to choosing a type of instrument for use with our system it was also necessary to choose the manufacturer. As we had eventually mailed inquiries to over seventy manufacturers we found ourselves faced with a very wide choice of commercial products. The designs of the majority of these transducers had a feature or employed a principle that either prohibited the measurement of a static pressure or that limited the resolution of the system. Even among transducers of the same or of similar designs, however, it was soon noted that there was a wide divergence among capabilities and costs so it was not difficult to establish preferences between manufacturers. We also interviewed users of instruments from two manufacturers (Dynamic Instruments Company and Schaevitz Engineering) and the information we received proved very useful.

The remainder of this section will be devoted to eight basic transducer designs ending with a detailed discussion of the chosen Schaevitz transducer. In each of these discussions will be found a description of the construction and operation of the design, basic instrumentation requirements, and an evaluation of the instrument with respect to the requirements which we have just discussed. It will be found that all of the designs considered lacked at least one of the advantages of the Schaevitz transducer, but in spite of this clear choice, considerable effort was made to insure that no instrument more suitable than the Schaevitz instrument could be obtained. (Table II-2 summarizes the characteristics of the various transducer systems.) The eight basic designs are the following:

1. Resistance
2. Strain Gage
3. Piezo-electric
4. Variable Capacitance
5. Variable Reluctance
6. Pressure-sensitive Resin
7. Vibrating String
8. Linear Variable Differential Transformer

1. The Resistance Transducer - This instrument presents to an input current a resistance which varies with pressure. The diaphragm can be either a flat plate, a capsule, or a bellows; the part of the transducer that converts diaphragm deflection to resistance can be one of several types of potentiometers, some of which are listed

TABLE II-2 Summary of Characteristics of Typical Transducer Systems (Part 1)

Type of Transducer	Does the system in use with the transducer meet the resolution requirement of .03 in. water?(1)	Output linear with input?(6)	System capable of following low frequency input fluctuations?
Resistance			
Wire-wound Potentiometer	No	Yes	Yes(5)
Carbon strip potentiometer	(2)	Yes	Yes(5)
Strain Gage	Yes(3)	Yes	Yes
Piezo-electric	No(4)		
Variable Capacitance	Yes	No	Yes(5)
Variable Reluctance	(2)	Yes	Yes(5)
Linear Variable			
Differential Transformer	Yes	Yes	Yes
Pressure-Sensitive Intermetallic Resin	Yes	No	Yes
Vibrating String	No information available - unable to contact manufacturer		

- (1) Exact figures not given as resolution depends upon the capabilities of the instrumentation for most systems.
- (2) Literature from manufacturer indicates possible ability to comply with the requirement but unable to obtain guarantee from manufacturer or representative.
- (3) Amplification definitely required.
- (4) Does not measure static pressures, merits no further consideration.
- (5) Considerable difficulty may be encountered in this respect if manual bridge matching is used in instrumentation.
- (6) Deviation of 1% full range or less.

TABLE II-2 Summary of Characteristics of Typical Transducer Systems(Part 2)

Type of Transducer	Measure differential liquid pressure?	Over-pressure limitations before possible damage.(7)	Preferred Instrumentation.	Cost (8)
Resistance				
Wire-wound Potentiometer	No	50%-500%	A.C. or D.C. resistance	(T)\$80up
Carbon strip potentiometer	Yes	20%	A.C. or D.C. resistance	(T)\$315
Strain Gage	(9)	14,900%	A.C. or D.C. resistance(3)	(T)\$190up
Piezo-electric				
Variable Capacitance	No	100%-900%	A.C. capacitance	(S)\$800up
Variable Reluctance	Yes	100%-400%	A.C. inductance	(S)\$565up
Linear Variable Differential Transformer	Yes	100%-2500%	A.C. voltage measuring	(T)\$210-\$275
Pressure-Sensitive Intermetallic Resin	No		D.C. resistance	(T)\$75
Vibrating String	No information available - unable to contact manufacturer			

(3) Amplification definitely required.

(7) With respect to working range, above high end of working range.

(8) Figures approximate, modifications may increase these figures considerably.

(S) Transducer with instrumentation and power supply

(T) Transducer only

(9) A Dow Silicone fluid can be used as an intermediate fluid between two water heads on many transducers of this type. Some recent designs are capable of handling non-corrosive liquids on both sides of the diaphragm.

below:¹⁰

1. Rotary displacement potentiometer
 - a. Fine resistance wire wound about a circular hoop, or
 - b. Helical strip resistance element
2. Linear displacement potentiometer
 - a. Fine resistance wire wound about a straight spool, or
 - b. Carbon strip

The rotary displacement potentiometer pickup requires a linkage assembly between it and the diaphragm in order to convert linear motion into rotary motion. Unless linear displacement amplification is desired, a direct linkage between the diaphragm and the pickup of the linear displacement potentiometer will provide sufficient connection between the two. Those potentiometers which use fine resistance wire are commonly known as "wire-wound precision potentiometers."

Unlike most transducers studied, the resolution of a system using a resistance transducer will find its limitation in the transducer itself. Usually this resolution is about .3% of full scale pressure and the limitation is the result of either hysteresis, friction, backlash, or step resolution.

Friction is one limitation usually associated with resistance transducers; it can exist between the sliding electrical pickup and the resistance element. Its presence can also be expected at all junction points of linkages. It appears reasonable, therefore, that a certain minimum

change of pressure will be required before static friction is overcome and a change of electrical resistance is observed. Backlash, of course, is characteristic of linkages. If one desires low backlash and linkage friction, he may have to sacrifice badly needed linear displacement amplification and avoid the use of a rotary potentiometer in the transducer.

The fourth-named limitation, step resolution, is a characteristic peculiar to wire-wound potentiometers. Each step in the calibration curve occurs when the electrical pickup slides over one additional wire. Use of small gage wire, of course, reduces the magnitude of this limitation. The smallest diameter wire usually used appears to be one mil.

The vast majority of the resistance transducers available from over a dozen firms were variations of the wire-wound precision potentiometer type. On account of stepped resolution, none of these wire-wound potentiometer transducers were able to obtain pressure resolutions better than .16 inches water (compared with our minimum resolution requirement of .03 inches water). The minimum operating range of these transducers was 0-2 psi (0-55.4 inches water). One resistance transducer manufactured locally (Computer Instruments Corporation) used a carbon strip potentiometer having infinite resolution, and while the advertized resolution appeared to be two one-hundredths

inches water limited by repeatability, the manufacturer was unwilling to give us a guarantee regarding this resolution. As might be expected, the operating range of this transducer was somewhat lower, 0 -.5 psi (0-13.85 inches water.)

With regard to the characteristics other than resolution and operating range, the first of these, linearity, is not one normally associated with potentiometers in a circuit. In an effort to make the transducer linear and to improve system sensitivity, we found that many manufacturers would construct instruments with varying resistances in order to accommodate the impedance matching requirements of the customer's instrumentation.

Most wire-wound potentiometer transducers did not have an ability to measure liquid pressure differences, but with regard to dependability and ruggedness the figures concerning maximum pressure before damage varied widely. The carbon strip transducer, in contrast did have an ability to measure water pressure differences. The manufacturer indicated, however, that it could withstand but .1 psi (2.77 inches water) above full scale range before damage might possibly occur, a rather low margin of safety.¹¹

Instrumentation of resistance transducers is not difficult; either direct or alternating current instrumentation may be used. If the transducer is used with direct current, the only component of the instrumenta-

tion used will be an ammeter or possibly a voltmeter. Another advantage of using direct current instrumentation lies in the fact that direct current would be subject to little voltage loss and to no atmospheric interferences in the lines between the moving transducer and stationary instrumentation and power supply. Direct current instrumentation, on the other hand, requires careful impedance matching for optimum linearity and sensitivity between transducer and instrumentation thus somewhat limiting the ability of the designer of the system to substitute different components in his instrumentation. In the event that an increase of sensitivity is desired, there would be the need for a direct current amplifier which is more costly than an alternating current amplifier.

Substitution of alternating current instrumentation for direct current instrumentation represents a possible exchange of advantages and disadvantages. While alternating current voltages with purely resistive loads are generally subject only to the same losses as direct current voltages, shielded cable between the moving and stationary parts of the system should be used, particularly if low voltages or low currents are involved. This precaution is intended to prevent spurious voltages from being induced in the cable on account of nearby electromagnetic disturbances such as power lines, transformers,

electrical machinery, etc. Alternating current voltages, however, are easily amplified and component impedance matching in alternating current circuitry is usually accomplished with greater ease than in direct current circuitry.

The costs of wire-wound precision potentiometer transducers are modest, generally below \$100. The carbon strip transducer, on the other hand, is priced at \$315 which is close to the \$325 price of the Schaevitz transducer. Two of the manufacturers of the wire-wound precision potentiometer transducer were:

Bourns Laboratories, Inc.
Riverside,
California

Colvin Laboratories
364 Glenwood Avenue
East Orange, New Jersey

The manufacturer of the carbon strip potentiometer transducer described above was

Computer Instruments Corporation
92 Madison Avenue
Hempstead, New York

2. The Strain Gage Transducer - The common characteristic of the resistance and strain gage transducer is the fact that the deflection of a diaphragm effects a change of resistance in a component within the transducer. One relatively simple design of a strain gage transducer of low sensitivity uses strain gages mounted on the reverse side of a flat plate diaphragm;¹² a more sensitive instrument uses a bellows and linkage which is connected to four strain gages installed as a four-active-arm Wheatstone

Bridge. In this latter instrument, any expansion or contraction of the bellows will alter an output voltage that appears at the transducer output terminals.

All strain gage transducers have stepless or infinite resolution so the system resolution is determined by the capabilities and the settings of the instrumentation components. One transducer employing the Wheatstone Bridge is the .1 psig (2.77 inches water) full scale Model PT14-01 Dynisco (Dynamic Instrument Company, Incorporated) transducer which gives a full scale output voltage of 18 millivolts (for six volts input) so for our desired .03 inches resolution, the instrumentation must be capable of resolving 195 microvolts.¹³ This matter will be discussed further in the discussion of strain gage transducer instrumentation; with a suitable amplifier or with a high sensitivity indicator suffice it to say that our .03 inches water resolution requirement can be realized.

The Dynisco transducer in question has adequate linearity, .5% full scale, but it is incapable of measuring water pressure differences. This drawback could have been avoided, however, by the use of one of the high-dielectric Dow Silicones as an intermediate liquid between two heads of water. The Dow Silicones are available at varying viscosities, and it is considered good practice to use this intermediate fluid on both sides of the diaphragm. The intermediate fluids, of course, are separated from the

water by a loose membrane. Very recently strain gage transducers have appeared on the market that are capable of handling net pressures of non-corrosive liquids. In one of these designs a linkage immersed in the liquid on one side of the bellows passes from its connection with the bellows through a watertight opening to the strain gage rosette. Time will tell whether or not leakage problems will develop.

Literature concerning the Dynisco transducer indicated a maximum pressure before damage occurred to the diaphragm of 15 psi (416 inches water) with a factor of safety of unity. In an interview with Mr. Chester Grosch of the Davidson Laboratory it was learned that while a resolution down to .001 inches water was realized, a number of these transducers had to be returned to the manufacturer for various reasons.

The instrumentation requirements of the strain gage transducer were found by us to be similar to those of the resistance transducer, but it has just been noted that the instrumentation used with this instrument must be able to resolve voltages of considerably less than one millivolt. The most sensitive indicator available at Webb Institute is the Hickok model 675-A cathode-ray oscilloscope, and our experience revealed that the best resolution that we could obtain with it is 220 microvolts. It appeared to us, therefore, that with a small

amount of amplification, a system using the Dynisco transducer should be capable of a pressure resolution of less than .01 inches water.¹⁴

Another note of caution should be inserted at this point as we are now discussing a system which uses low magnitude voltages and voltage changes. Even with a good amplifier or vacuum tube voltmeter, considerable difficulties were encountered by the authors in handling and measuring voltages and voltage changes below one millivolt while working at the David Taylor Model Basin. Voltage readings tended to be unstable on the meters and waveforms on the oscilloscope showed the presence of unwanted frequencies. It is not known whether these difficulties occurred from the building line current, from unstable indicators or power supplies (we tried several of each), or from spurious frequencies generated in the ninety feet of shielded cable between the transducer that we were using at the time and the other system components. It should be enough to say that for us involvement with low voltage equipment in a "home-made" instrumentation arrangement was to be avoided. Many laboratories, however, are well equipped with instrumentation specifically designed for use with strain gages, a probable explanation for their apparent widespread use.

The prices of strain gage transducers vary widely but the Dynisco Transducer described above costs approximately \$350. The manufacturers of strain gage transdu-

cers are

Dynamic Instrument Company
42 Carleton Street
Cambridge, Massachusetts

Statham Instruments, Inc.
12401 West Olympic Blvd.
Los Angeles 64, Calif.

3. The Piezo-electric Transducer - A piezo-electric transducer is a single-element transducer suitable only for the measurement of the frequency of a fluctuating pressure. While no piezo-electric transducer could possibly be used for our project, a brief discussion of this design is appropriate as a matter of general interest and on account of its wide use in industry and in research.

The single element of this transducer is a crystal of a salt having piezo-electric properties. When one of these salts is subjected to a change of pressure, external charges of opposite polarity will appear on opposite sides of the crystal. All that is needed, then, is the application of electrodes to the opposite sides and the amplification of the generated voltage for display or measurement.¹⁵

Aside from their apparent inability to measure static pressures, piezo-electric transducers definitely would have been inappropriate for our system as these crystals are normally limited in use to pressures somewhat greater than those we hoped to be able to measure in the experiments intended for our desired transducer. For experiments involving pressure variations of pressure ampli-

tudes such as ours, a variable capacitance transducer is generally employed.

4. The Variable Capacitance Transducer - This type of transducer, known also as the capacitance transducer, is available in a very wide range of resolutions including that which we required. The design is simple and its principle of operation easily understood. The diaphragm of this transducer is likely to be a circular flexible flat plate clamped around the edge and electrically insulated from the structure. This flat plate diaphragm acts as one of the plates of a simple two-plate air dielectric capacitor. The other plate of this capacitor is a rigid surface, possibly an actual part of the structure of the transducer. A change of pressure causes a change of diaphragm deflection and likewise a change of capacitance exhibited by this transducer.

Unlike most other instruments, the variable capacitance transducer can be designed from theoretical relationships. Therefore, if we had been unable to find a satisfactory instrument on the market, it might have been entirely possible to design one for manufacture. From the relationships listed below, it should be apparent that there is a wide range of sensitivities and resolutions for which these transducers can be constructed;¹⁶

1. If the deflected diaphragm is regarded as a

family of concentric disks, the sensitivity is found to be (assuming a dry air di-electric and a Poisson's ratio of .3):

$$\frac{\Delta C_p}{p} = .0402 \frac{r^6}{d^2 E t^3} \quad (A)$$

where $\Delta C_p/p$ is change of capacity, micromicrofarads per psi change of pressure,
 E is Young's modulus, psi
 t is thickness of the diaphragm, inches
 r is radius of the diaphragm, inches, and
 d is the spacing between the plates at zero deflection, inches.

2. In the no-load condition when the plates are parallel, the capacitance (using a dry air dielectric) is

$$C = 0.225 A/d \quad (B)$$

where C is capacitance, micromicrofarads, and
 a is the area of each plate, square inches.

3. Capacitor transducers with high sensitivities tend to have low resonant frequencies:

$$f = 0.492 \sqrt{\frac{Eg}{\rho}} \frac{t}{r^2} \quad (C)$$

where f is the natural frequency in air, cycles per second,
 g is acceleration due to gravity, inches per second squared, and
 ρ is weight density, pounds per cubic inch of diaphragm material

Any deviation from our assumption of perfect clamping along the edge of the diaphragm in equation (C) reduces the resonant frequency somewhat as does the exposing of the pressure face of the diaphragm to a liquid. In order to prevent difficulties in making output readings

the resonant frequency of the diaphragm should be at least ten times that of the highest frequency vibrations one would expect in his input pressure.

From the foregoing it can be reasoned that the limitations placed on the sensitivity for a proposed design are

1. the ability of the manufacturer to obtain thin plates and narrow plate spacing,
2. the maximum permissible diameter of the diaphragm,
3. the lowest permissible resonant frequency,
4. the capability of the instrumentation to resolve a change of capacitance, and
5. the ability of the manufacturer to insure tight clamping along the diaphragm circumference and to prevent the entry of moisture into the dry air dielectric.

Example: As a feasibility study, find the diameter, no-load capacitance, and resonant frequency for a capacitance transducer having a downmetal diaphragm .5 mils thick and a plate spacing of 3 mils. The impedance bridge available in the Webb Laboratory can resolve 10 micromicrofarads and it is desired to resolve .02 inches water with the transducer.

$$.02 \text{ inches} \times 1 \text{ psi} / 27.71 \text{ inches water} = .721 \times 10^{-3} \text{ psi}$$

$$\text{In Equation (A) Let } d = 3 \times 10^{-3} \text{ inches, } E = 6.5 \times 10^6 \text{ psi}$$

$$\rho = .065 \text{ #/in.}^3 \quad t = 5 \times 10^{-4} \text{ inches}$$

$$\frac{10}{.721 \times 10^{-3}} = .0402 \quad \frac{1}{9 \times 10^{-6}} \times \frac{r^6}{6.5 \times 10^6} \times \frac{1}{125 \times 10^{-12}} \quad \begin{array}{l} r^6 = 2.523 \times 10^{-3} \\ r = .369 \text{ in.} \\ 2r = .738 \text{ in.} \end{array}$$

$$\text{From Equa. (B): } C = \frac{.225 \pi (.369)^2}{3 \times 10^{-3}} = .321 \times 10^2 = 32.1 \text{ M}\mu\text{f}$$

$$\text{From Equa. (C): } f = .492 \sqrt{\frac{6.5 \times 10^6 \times 386}{6.5 \times 10^{-2} \times .369^2}} = 35.6 \text{ cps}$$



It appears that this transducer is entirely suitable with regard to pressure resolution as long as we do not encounter significant components of pressure fluctuations that might induce resonant vibrations. We should note, however, the capacitance of the transducer capacitor at no-load, i.e., $32.1 \mu\text{f}$ compared with the $10 \mu\text{f}$ resolution capability of the impedance bridge. According to Roark¹⁷

$$y_{\text{center}} = \frac{3W(m^2-1)a^2}{16\pi E m^2 t^3} = \frac{3}{16} p \frac{91}{Et^3} r^4 \quad \text{assuming } \frac{m^2-1}{m^2} = .91$$

where W is the total distributed force on the flat plate, pounds,

y is the deflection of the center of a circular flat plate, inches (edges fixed, uniform load over the entire surface), and

m is the reciprocal of Poisson's ratio.

For the dimensions of the capacitor in the feasibility study, i.e., $r = .369 \text{ in.}$ $t = 5 \times 10^{-4} \text{ in.}$ $E = 6.5 \times 10^6 \text{ psi}$

a pressure of .02 inches water would deflect the center of the diaphragm

$$\frac{3}{16} (721 \times 10^{-3}) \frac{91 (.369)^4}{(6.5 \times 10^6)(5 \times 10^{-4})^3} = .283 \times 10^{-2}$$

which is almost equal to the diaphragm spacing. Obviously, from a standpoint of operating range (and linearity) this design would have been entirely unsuitable for our use.

Table II-3 does give a comparison of two existing capacitor transducers. With the proper design of the transducer and sufficiently accurate and sensitive instrumentation, however, it should have been possible to design

Table II-3 A Comparison of Two Capacitance
Transducers^{18,19}

Manufacturer	Technitrol Engineering Philadelphia, Penna.	David Taylor model Basin
No-load capacitance	40 μf	44.1 μf
Sensitivity	.0167 $\mu\text{f}/\text{psi}$	$\sim 2.23 \times 10^{-8} \mu\text{f}/\text{psi}$
Resonant frequency in air (cycles per second)	3000 p/u	100,000
Normal operating range	$\pm .0387 \text{ psi}$	$\pm 10 \text{ psi}$
Maximum pressure before damage	$\pm .387 \text{ ps}$	$\pm 80^+ \text{ psi}$

or obtain a capacitor transducer system satisfactory to use from the standpoints of operating range and resolution. The output would be linear for a small region²⁰ near the no-load point but this transducer would be incapable of handling differential water pressures. As long as the diaphragm is protected from abuse, the transducer should be regarded as fairly rugged in view of its basically simple construction and relative lack of moving parts. Complete watertightness around the diaphragm should be maintained (otherwise frequent recalibration will be necessary) and precautions should be taken to prevent excessive corrosion of the thin diaphragm. There are several methods by which a capacitance transducer may be instrumented. Two of these methods in-

volved the use of a bridge in which the transducer acts as one of the four capacitor elements, either directly or through a pair of transformers:

1. A calibrated variable capacitor acting as the second arm of the bridge may be varied until the bridge unbalance current is reduced to zero or "nulled." The pointer reading for this variable capacitor could then be related to transducer output, hence pressure input. This arrangement would permit measurement of a steady pressure or of the maxima or minima of a repetitive pressure fluctuation as well as the frequency. Studies of non-repetitive fluctuations, however, would be extremely difficult if not impossible.

2. The capacitance transducer can be placed in a bridge containing three other fixed value capacitors. The magnitude of the bridge unbalance current, therefore, would be a function of the transducer capacitance. This arrangement permits a study of the shapes of pressure waves at frequencies limited only by the resonant frequency of the diaphragm. In order that the bridge unbalance current accurately reflect the input pressure to the transducer, it would be necessary that the signal generator have good voltage and frequency stability.²¹

A third possible method of instrumenting this type of transducer does not use a bridge. Instead, the variations of the transducer output capacitance can be used to frequency modulate a small transmitter. In actual practice the capacitance transducer is more likely to be used for the measurement of low pressure frequencies than for the measurement of low pressure amplitudes.

All transducer systems that involve the measurement of capacitive or inductive reactance present many potential difficulties concerning shielding. A detailed discussion of this subject would be quite lengthy; the au-

thors will try to be as brief but as thorough as possible.

Cabling between the various components of any system presents resistive, capacitive and inductive impedances to alternating currents as well as presenting an antenna for electromagnetic disturbances from the atmosphere. The resistances in these cables vary only with temperature and this is the only impedance that is likely to have a marked effect on a resistively loaded alternating current. Unlike resistance, the capacitance and inductance of a cabling is quite likely to vary with its looping and unlooping as the carriage proceeds down the tank. Reactances add vectorially zero degrees or 180 degrees to the output reactance of one of these transducers in question thus making it extremely difficult to compensate for line reactance distortion.

The foregoing problem concerning shielding of capacitance transducer systems is aggravated by the high values of reactance exhibited by the transducer.²² A high capacitive reactance load at the end of a transmission line results in significant and varying unknown amounts of capacitive line leakage. Aside from increasing transducer capacitance (to draw the current through the length of the cable to the transducer rather than across it through leakage) and decreasing the length (and unknown capacitance) of the line, the best remedy for this problem is the finding of the optimum frequency with respect to transducer capacitance and to the system's shielding.²³ Another compromise must be made con-

cerning the operating voltage.²⁴

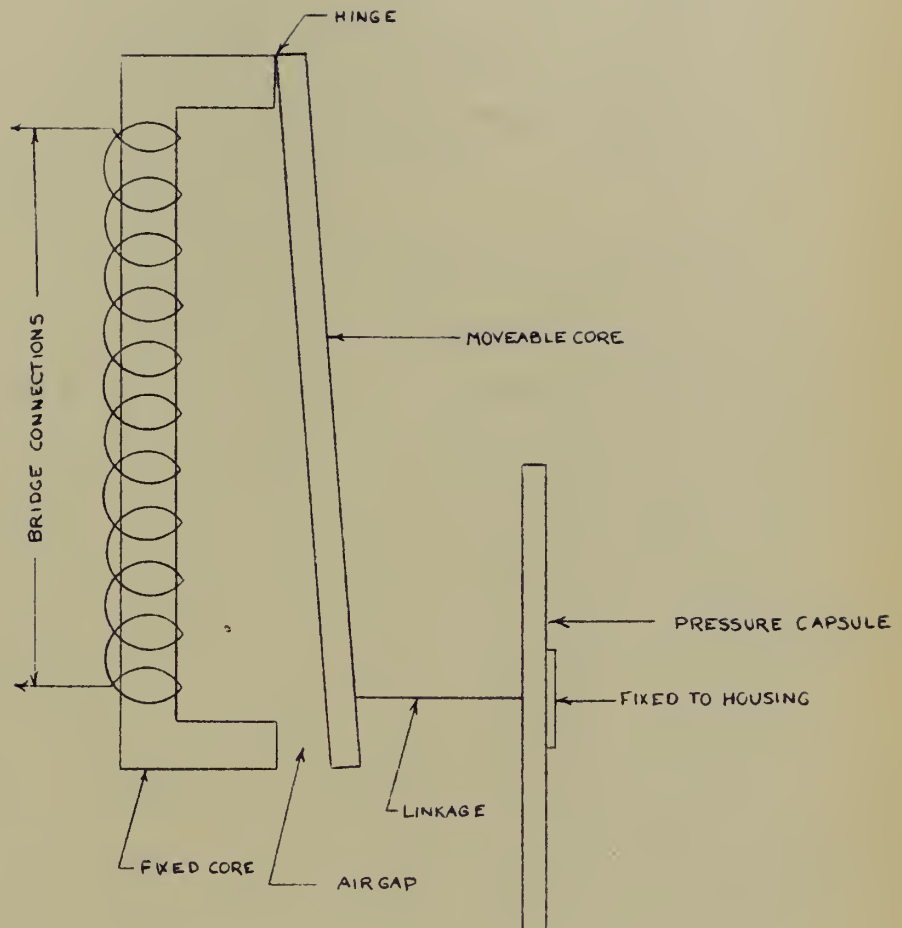
The frequency utilized for a capacitance transducer system is likely to be somewhere in the radio frequency range (above 20 kilocycles).²⁵ The art of shielding for high frequencies is quite uncertain - as the authors have learned to their regret - and most capacitance transducers are purchased along with instrumentation specifically designed for the transducer. The price of a complete system is generally around \$800. There are several manufacturers of this type of transducer and associated instrumentation. Three of these firms are

Photocon Research Products
421 North Altadena Drive
Pasadena, California

Southern Instruments Limited
Frimley Road
Camberley, Surrey, England

Technitrol Engineering Company
1952 East Allegheny Avenue
Philadelphia 34, Pennsylvania

5. The Variable Reluctance Transducer - There are a large number of designs of variable reluctance transducers as well as names, e.g., variable inductance transducers or simply inductance transducers. All of these instruments, however, exhibit an output inductive reactance that varies with pressure. The simplest design (illustrated in Figure II-5) consists of a diaphragm and fixed and moveable portions of an iron core forming a magnetic loop. One end of the moveable portion is hinged to an end of the fixed core; the other end is connected by a linkage to the diaphragm leaving a small air gap between it and



SIMPLIFIED VARIABLE RELUCTANCE TRANSDUCER

the other end of the fixed core. A deflection of the diaphragm, therefore, varies the width of the air gap thus changing the reluctance of the magnetic circuit. These variations of reluctance then vary the reactive impedance of a coil wound around the core, thus a pressure change is converted into a change of inductive reactance within the transducer.

Replies to our inquiries were received from five manufacturers of variable reluctance transducers. The information following pertains to a system manufactured by Ultradyne which we regarded as quite promising. The transducer, power supply and instrumentation (less the indicator) sold as a complete unit have a linear direct current output and the transducer is capable of handling differential liquid pressures. The system in question, the model DCS-4 pressure to voltage system including a model S-60 transducer, can resolve .01 inches water and has a full scale range of 0-.1 psi (0-2.77 inches water). The diaphragm is capable of withstanding five psi (about 139 inches water) without recalibration and at least 50 gravities of acceleration on any axis.²⁵

The instrumentation, of course, must be capable of measuring inductance; one of the two bridge arrangements suggested in the discussion of capacitance transducer instrumentation may be used with the substitution of the capacitor arms by inductor arms. Some shielding problems

may exist, but the impedances (hence the required generator frequencies) are considerably lower than those associated with capacitance transducers. As in the case of the capacitance transducers and the Ultradyne transducer, it is usual practice to purchase the instrumentation and power supply with the transducer.

Prices of inductance transducers vary widely, the Ultradyne assembly of power supply, transducer and instrumentation less the indicator costs about \$565. Three of the five manufacturers of inductance transducers from whom we received replies were the following:

Crescent Engineering and
Research Company
5440 North Peck Road
El Monte, California

Ultradyne, Incorporated
2630 San Mateo northeast
Albuquerque,
New Mexico

Wiancko Engineering Company
255 North Halstead Avenue
Pasadena, California

6. The Pressure-sensitive Resin Transducer - This transducer is similar to the resistance transducer as the output resistance of the instrument changes with pressure. These instruments use one of several pressure-sensitive intermetallic resins placed behind an exposed gold coated "mylar" diaphragm. This transducer is extremely sensitive. One design having a full scale range of 0 to 3.06 inches water registers a change of about 130 ohms per .02 inches water and with a sufficiently sensitive resistance bridge a resolution of .0006 inches

water can be obtained according to the manufacturer.

The output is nonlinear, the instrument is incapable of measuring differences in water pressure, and difficulty may even be encountered if use of a gas reference system is desired. The only power supply required is a dry cell; the only required instrumentation is a milliammeter. The transducer can be obtained from Clark Electronic Laboratories of Palm Springs, California, at a price of \$75.

7. The Oscillating String Transducer - This transducer is normally a force transducer and while it is unlikely to have sufficient sensitivity and resolution for our purposes when used with a diaphragm, its principles of operation suggest some interesting possibilities. In this instrument, a vibrating steel wire string passes through an air gap of an inductive pickup system thus varying the magnetic flux within the air gap. A suggested arrangement would be the mounting of one end of the wire string on the end of a spring and the other end on a point of the diaphragm. As the resonant frequency of a vibrating string varies as the square root of the tension, nonlinear voltage output variations can be expected from pressure changes. The system is regenerative as the output is amplified and a part of the output is then used to maintain vibrations of the string at the appropriate natural frequency.²⁶

No quantitative information on this design has been found; the only manufacturer of this type of instrument known to us has apparently gone out of business.

* * *

Before discussing the type of transducer that was finally selected, it would be well to present a brief review of the transducers and the systems just discussed. We are particularly concerned, of course, about any features that might have precluded the purchase of any one of them for use at the Webb Towing Tank:

1. Resistance - Purchase expenses would have been modest but all designs appeared to have inadequate resolution.

2. Strain gage - The desired resolution of the Dynisco transducer system could have been obtained only with some amplification. All transducers of this type known to us at the time of selection were limited to the measurement of water pressure on only one side of the diaphragm. The output was linear and the purchase price would have been about the same as that of the chosen Schaevitz transducer.

3. Piezo-electric - This instrument was limited in use to the frequency measurement of a high amplitude pressure fluctuation.

4. Variable Capacitance - The instrument could have been designed to suit our resolution and pressure range requirements. The instrumentation for the instrument, however, would have been difficult to design and to use. In addition, the instrument was incapable of measuring liquid net pressures, the output was generally nonlinear, and the cost of the entire system would have been considerably higher than that of any other system.

5. Variable Reluctance - The Ultradyne system appeared to have the capabilities required though we would have been unable to amplify conveniently its direct current output. The total cost of the system

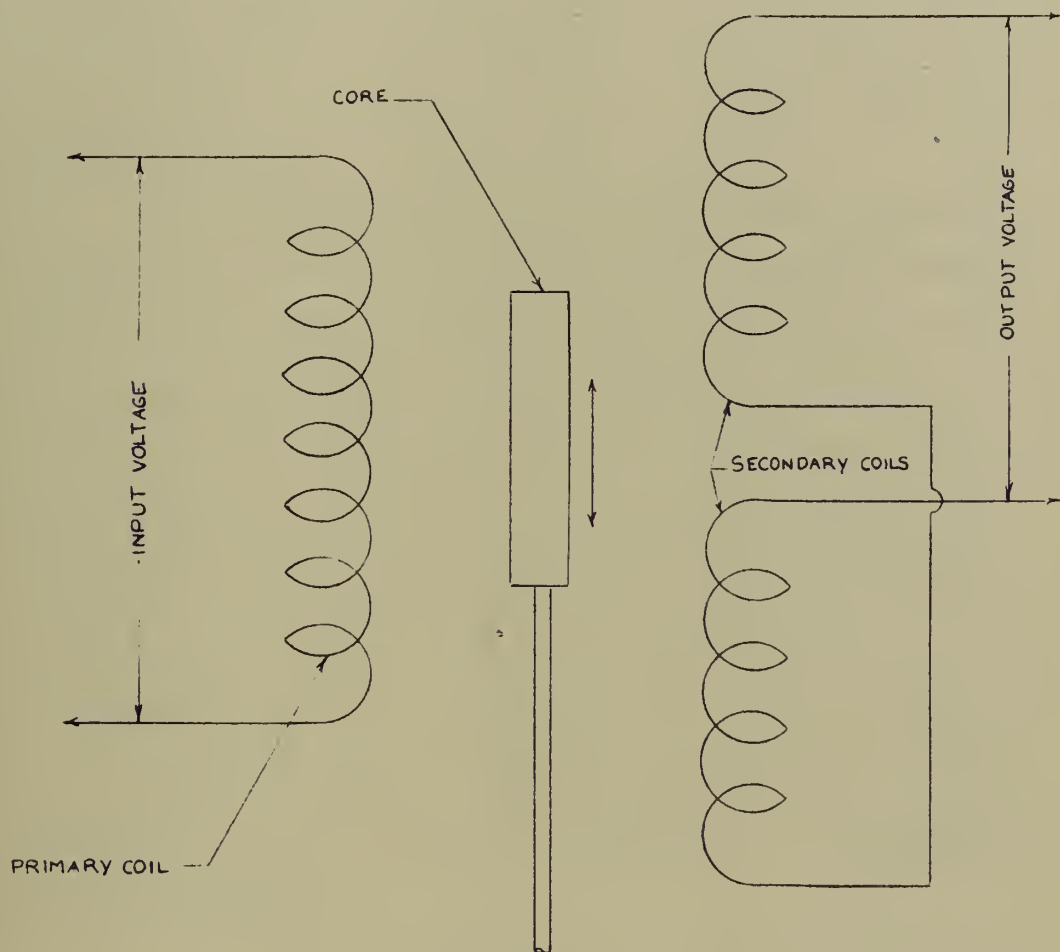
would probably have been somewhat higher than that of the Schaevitz transducer that we finally decided to procure. The useful range is limited to 0-2.77 inches water without backup pressure, a bit less than what we would have liked.

6. Pressure-sensitive resin transducer - This transducer had a limited operating range (0-3.06 inches water), it was incapable of measuring net liquid pressure, and the output was nonlinear.

8. The Linear Variable Differential Transformer Transducer -

A linear variable differential transformer (LVDT) transducer is an instrument that registers an alternating current output voltage that varies in amplitude with pressure. The diaphragm can be a flat plate, bellows or pressure capsule, but the pressure capsule appears to be the one most suitable for effecting a combination of compactness and sensitivity. The component of this transducer that is sensitive to linear displacements is a LVDT, an assembly of a moveable nickel-iron core surrounded by three windings aligned axially. The middle coil, the primary coil, is straddled by two identical secondary coils connected in series opposition. (See Figure II-6.)

The operation of the LVDT is quite easy to understand. The series opposing connections of the secondary windings causes two induced voltages to "buck" each other or to add vectorially 180° with respect to each other. At the so-called "null-point" of the nickel-iron core the voltage of each winding is equal to each other and across the output of the differentially con-



LINEAR VARIABLE DIFFERENTIAL TRANSFORMER

nected windings is a zero voltage. Any displacement of the core changes proportionately the voltages generated in the windings - one increases while the other decreases - and the vector sum that appears at the output will vary in magnitude with the numerical difference of these induced voltages.

The LVDT appears to be an amazingly sensitive linear displacement measuring device; with the test stand micrometer (See figure III-2) a linear displacement resolution of better than .05 mils from the calibration curve was obtained (See figure II-11). The transformer and consequently the transducer has good linear output characteristics (about 1% of the full scale value) through most of the operating range. There is one important aspect of the LVDT that may adversely affect the linearity near the null point, the loss of linearity being the result of "null voltage," a concept that will now be explained.

It was noted earlier that the series opposing connections will cause the two induced secondary voltages to add vectorially to a zero magnitude at null-point or at the null position of the core. The two induced voltages, however, are not exactly 180° out of phase with each other so when null point is reached one finds a voltage of low amplitude having a phase difference from the phase of each of the two secondary voltages of just

under 90° .

Figure II-11 shows a plot of LVDT output voltage obtained for varying core axial displacements on either side of null. It is readily seen that there is a marked loss of linearity and sensitivity in the region near the null point, but for increasing displacements outside of this null region the linearity improves. There are a number of other possible explanations, however, for the existence of null voltage. Among them are

1. Spurious or harmonic frequencies from the power supply which are not completely reduced to zero amplitude at null point,
2. Unbalance in the fields of the two secondaries,
3. Capacitance coupling between the primary and secondary circuits, and
4. Stray resistance leakage between the primary and one or both of the secondary coils.²⁷

(Figure II-7 illustrates very well the oscilloscope presentation of a transformer output waveform that might occur while passing through the null point with the core. When these wave shapes appear in lieu of the desired horizontal line characteristic of zero input voltage, it becomes extremely difficult for the operator to determine whether

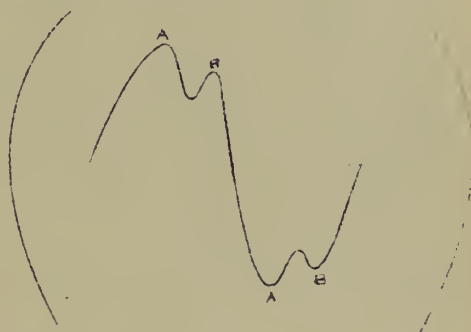


Fig.II-7. Typical oscilloscope waveform at null. As the core approaches and passes through the null position, peaks (A) may diminish in amplitude while peaks (B) will increase. Hence the null point would be difficult to locate.

or not he has reached the null point. If the operator were using a vacuum tube voltmeter, the minimum voltage reading or dip would not appear to be well defined on account of the loss of linearity and sensitivity near the null point; it would be necessary to pass the core through the null position several times before the location of null point could be determined with reasonable accuracy.)

One can take steps to both reduce null voltage and to avoid its undesirable effects. Two methods of reducing the magnitude of null voltage used by the authors were

1. The use of a filter at the output of the transducer or at the output of the amplifier, and
2. The connection of the ends of a rheostat to the output leads of the differential transformer and the connection of the remaining secondary winding leads to the pickup of the rheostat.

The above two steps, once taken, should eliminate well over 95% of the null voltage appearing at the output of the transformer or of the amplifier if used. The reduction of null voltage brings the linear range of the LVDT much closer to the null point and should permit satisfactory operation in a region where the operator will realize the highest percentage of voltage change for a given change of pressure input. The person who operates just outside of the null region is said to be operating "just off null."

In order to insure transducer operation in the region just off null (or in any other region of a plot of output voltage versus pressure input), the operator must have a

means whereby he can determine the point on the plot which he wants to be his "no-load" or starting point. There are a number of ways by which this may be accomplished:

1. Most LVDT transducers have a screw fitting that permits a linear displacement of the transformer in the direction of its axis. This manual adjustment has exactly the same effect on the generation of voltages in the secondary windings as does the linear displacement of the core caused by diaphragm deflection.
2. A controlled reference pressure may be applied to the reverse face of the diaphragm.
3. A second LVDT may be connected in series opposition with the transformer in the transducer. A displacement of either transformer core varies the output of the pair, hence manual displacement of the core of the additional transformer may be used for output voltage adjustment.

The utilization of a LVDT system at maximum effectiveness can be achieved only after the development (largely through trial and error) of good technique. Two factors which have an important bearing on the system sensitivity and resolution are the choices of input voltage and frequency to the transducer. While actual figures will vary according to the design of the LVDT, sensitivity increases with frequency leveling to an optimum of about twelve hundred cycles and thence to a gradual decline. (See Figure II-8.) In addition to the question of the location of the point of optimum sensitivity, there are several other considerations which pertain to the choice of the operating frequency:

1. An increase of frequency may raise or lower the null voltage, depending upon the design of the transformer.

2. At frequencies somewhat less than 1000 cps, the sensitivity of a LVDT will vary with input frequency thus necessitating a power supply with good frequency stability. Near the frequency of maximum sensitivity, variations of input frequency should have little or no effect on sensitivity, thus giving stable indicator readings for constant pressure inputs.

3. Line reactance effects increase with frequency.

4. Variable frequency power supplies and filters are quite expensive and savings may result from the purchase of a unit oscillator having one or two fixed output frequencies and of a single frequency filter. Use of these single frequency components, of course, may preclude the utilization of the frequency deemed most desirable.

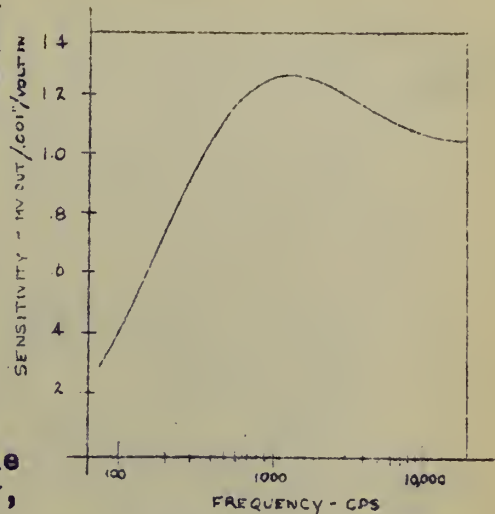


Figure II-8 Sensitivity vs. frequency of voltage input for a typical LVDT

While discussing the subject of input frequency, it should also be noted that the actual power supply output waveform will have harmonic and spurious components, and these components will appear in the null voltage. Elimination of the unwanted frequencies is accomplished by the use of a filter which in turn reduces system sensitivity and resolution.

As it is with the selection of operating frequency, the choice of transducer input voltage is the result of a compromise. The sensitivity of a LVDT at a specified

frequency is always expressed as (millivolts output) per (mil deflection)(volt input.) This implies increased sensitivity for increased input voltage.

Once again the operator must face certain practical considerations:

1. The output power of any power supply has its limits. As the power absorbed by the LVDT is proportional to the square of the voltage, the maximum voltage used by the LVDT may be determined by the capabilities of the power supply and by the number of transformers in use.

2. The heat generated in the coils varies as the square of the input voltage. Heat in turn increases wire resistance resulting in reduced output voltage and sensitivity, particularly for instrumentation having low impedance inputs. The increased generation of heat within a coil also increases the likelihood of burning out a winding.

Manufacturers of LVDT's specify an operating voltage since the question of the effect of heat on the windings is not easily studied by the operator. Unless overriding considerations are found in the capabilities of the power supply or from experience in the operation of the system, it is suggested that the rated voltage for the transformer be used. Good regulation of power supply voltage or current is essential for a stable transducer output.

The foregoing discussion was intended to impart a basic knowledge concerning the construction of and operation with the linear Variable differential transformer. With regard to the characteristics of the LVDT transdu-

cer, the remainder of this discussion will pertain generally to one particular instrument, the Schaevitz P476-A10 transducer purchased for our system. This instrument has stepless resolution and static water pressure tests were conducted by using a liquid reference pressure apparatus mounted with the instrument. It appeared that at least 90% of the system output readings obtained from these static tests diverged no more than .02 inches water without amplification of the transducer output but with the Hickok 675-A oscilloscope used as the indicator set at its most sensitive condition (See Figure IV-1a). No adverse effects accountable to hysteresis were noted and after considerable practice, good repeatability for the same power supply and instrumentation settings was noted even after an interval of several days. This particular transducer was intended for use with a pressure range of ten inches water net pressure on either side of no-load.

The system, moreover, exhibited good linearity at the normal 6.3 volts transformer input, and on account of the presence of a 1000 cps filter in the circuit and the connection of a potentiometer to the output leads of the secondary windings, the adverse effects on linearity near the null point that might had been attributable to null voltage were not observed. This

transducer had the capability of handling differential liquid pressures though difficulties were encountered in removing all of the air that had collected in the inside region of the capsule-type diaphragm after several days. The transducer should be fairly rugged as the only moving parts of the Schaevitz transducer were the diaphragm and the nickel-iron core. According to the Bristol Instrument Company, the manufacturer of the diaphragm, the diaphragm was able to withstand a maximum pressure or suction of 8 psi (222 inches water) before damage, a rather generous margin considering the designed operating range of plus or minus ten inches water.

During one of their two visits to the Davidson Laboratory, the authors were shown a Schaevitz P476-A10 LVDT transducer modified to vent air or to remove unwanted liquid (as the particular situation dictated) from the regions inside and outside of the capsule. In actual practice, however, it was found by Davidson Laboratory personnel that the addition of the vent for the inside region did not insure complete removal of unwanted air or water, perhaps on account of the corrugations of the capsule surfaces.

Primarily on account of the satisfactory performance of this transducer at the Davidson Laboratory,²⁸ it was decided to purchase a transducer similar to it. After a visit to the Bristol Instrument Company, two

suggestions were submitted to Schaevitz for further improvement of their instrument for our purposes (See Figure II-9.):

1. The venting tube for the inside region of the bellows should be ended near the uppermost point of the juncture of the diaphragm plates with the transducer in the normal position. Insertion of this tube would insure almost complete removal of air or water as desired from the region inside the capsule.
2. In place of the three mil thickness Ni-Span-C capsule presently used, a three mil thickness phosphor bronze capsule should be utilized. The substitution of phosphor bronze increases sensitivity about 60%, facilitates fabrication of a capsule with an inside air venting tube, and reduces corrosion. The Ni-Span-C capsule had the advantage of insensitivity to marked temperature changes, but on account of the fairly constant 80°F temperature of the Webb Towing Tank, the loss of this temperature insensitivity is one we could have well afforded.

Incidentally, the transducer that was finally obtained from Schaevitz was constructed from the plans used for the transducer purchased by the Davidson Laboratory (See Figure II-10.). A quotation based on the two suggestions submitted to Schaevitz Engineering quoted a price increase of over \$1000 per unit.

The instrumentation of any LVDT transducer is most likely to be an assembly intended to measure the amplitude of the transformer output voltage. The indicator of this instrumentation may be either a highly sensitive vacuum tube voltmeter (VTVM) or a cathode-ray oscilloscope (CRO). In addition to the indicator, there may be one or more of the following in the instrumentation:

1. An amplifier which would improve system sensitivity and resolution,
2. A filter which would impede the passage to the indicator frequencies other than the desired operating frequency, and
3. Rectifier circuitry and phase-sensitive networks which would enable the operator to determine instantly which side of null he is reading. Direct current indicators, i.e., a voltmeter or ammeter, would be used in this arrangement in place of alternating current indicators.²⁹

In lieu of a voltage or current measuring indicator, the suggestion was made that a LVDT null point sensing servo unit be used.³⁰ Time did not permit us to try this suggestion.

Prices of LVDT transducers vary from \$225 to \$300 for standard models; our transducer costed \$325. Four manufacturers of LVDT transducers are the following:

Automatic Timing and
Controls, Incorporated
King of Prussia,
Pennsylvania

International Resistance Co.
401 North Broad Street
Philadelphia 8,
Pennsylvania

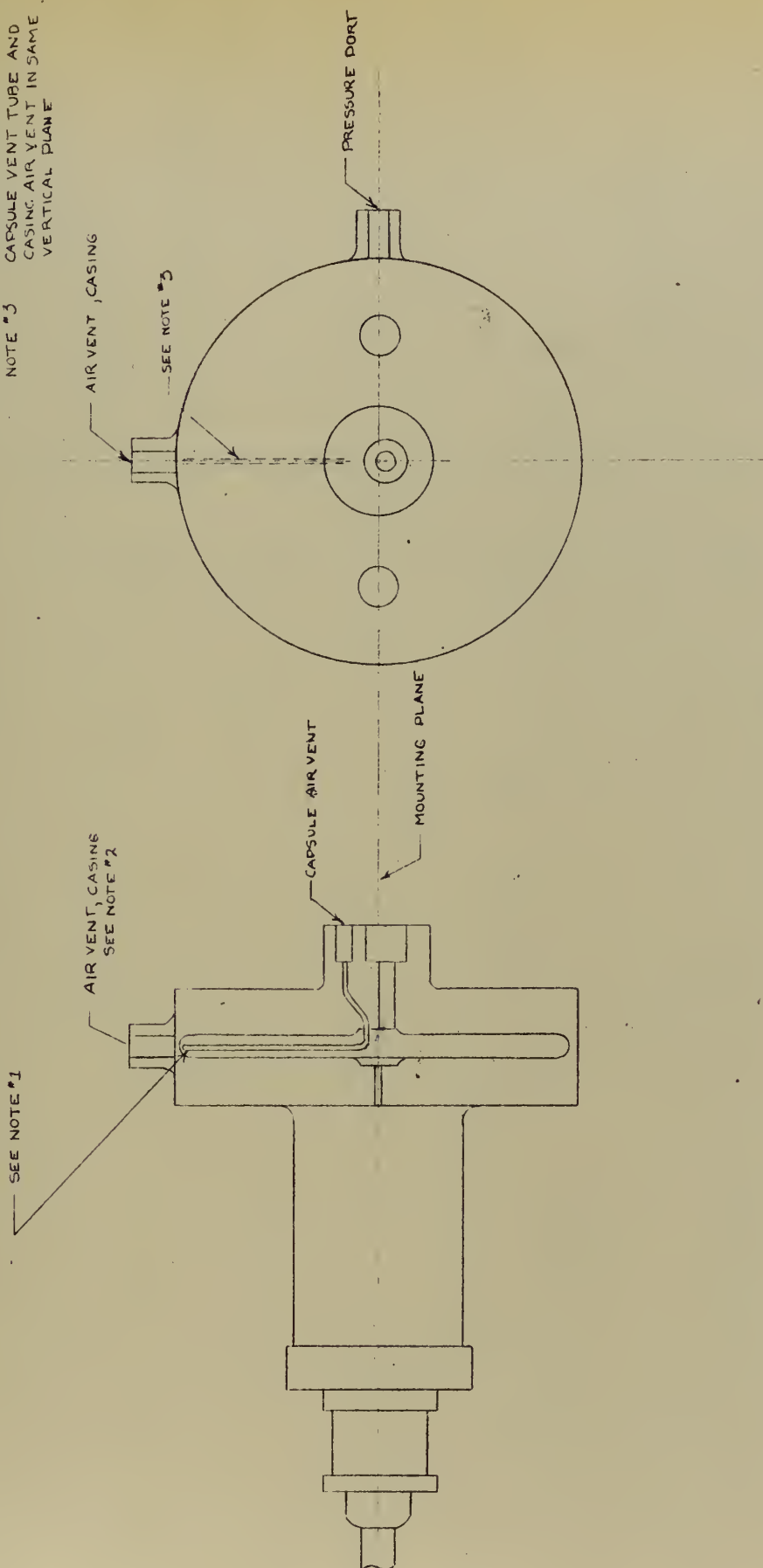
Sanborn Company
175 Wayman Street
Waltham 54, Massachusetts

Schaevitz Engineering
Camden 1,
New Jersey

NOTE #1 CAPSULE VENT TUBE
TO EXTEND TO ABOUT $\frac{1}{16}$ "
FROM I.D. OF CAPSULE.
TUBE O.D. SELECTED BY
MANUFACTURER SO AS
NOT TO INTERFERE WITH
DEFLECTION FOR AT LEAST
3" H₂O NEGATIVE PRESSURE
INSIDE CAPSULE

NOTE #2 DIMENSIONS SAME AS
PRESSURE PORT

NOTE #3 CAPSULE VENT TUBE AND
CASING AIR VENT IN SAME
VERTICAL PLANE

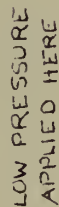


TRANSDUCER SKETCH
INDICATING
VENT MODIFICATIONS

NOT TO SCALE

10/23/60

FIG. II-9



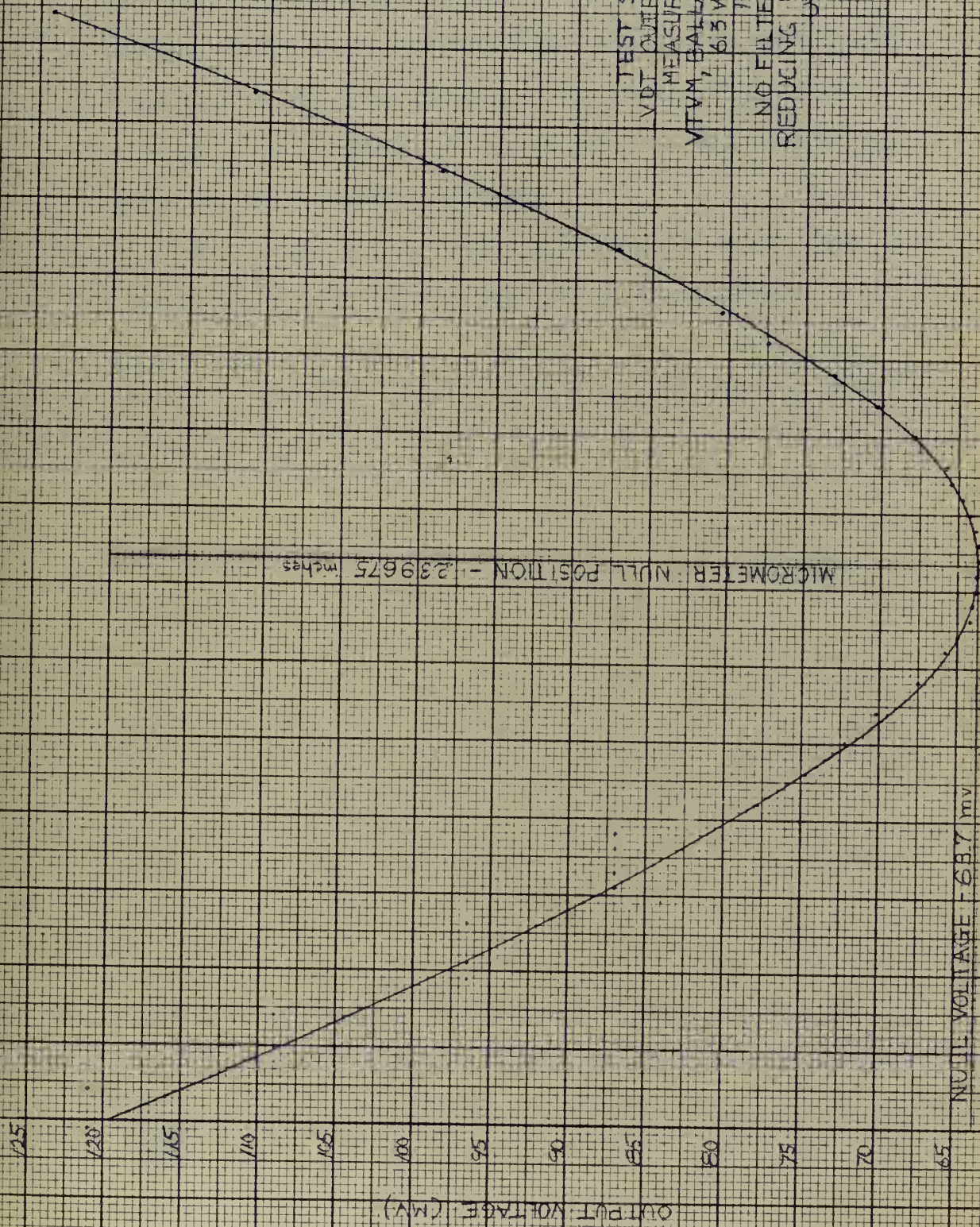
PRESSURE TRANSDUCER

TYPE 34E P476-A10

FULL SCALE 6-1-61

MATERIAL: HOUSING - 303 STAINLESS STEEL
DIAPHRAGM - NUSPANC

FIG II - 10



TEST STAND
VDT OUTPUT VOLTAGE
MEASURED BY
VTVM, BALLANTINE MODEL 300
6.3 VOLTS INPUT
1000 Ω
NO FILTER OR NULL
REDUCING POTENTIOMETER
USED

FIGURE II-11

Section III - Development of the Transducer System

The forming of the transducer system's power supply and instrumentation from their individual components was the product of considerable trial and effort over a period of several months. The resulting system proved to be capable of resolving the .02 inches water that we particularly desired.

The power supply and instrumentation of this final system consisted of the following components:

Power Supply 1. Audio oscillator, Eico Model 377, frequency range 20-20,000 cps, rated at .1 watt and 10 volts working into a 1000 ohm load.

2. Power amplifier, Heathkit model UA-2, frequency response of 20-20,000 cps, rated at 14 watts and 15 volts working into a 16 ohm load with .8 volts input.

Instrumentation 1. Terminal and switch box including a null reduction potentiometer.

2. Preamplifier, Heathkit Model AA-60, frequency response 20-20,000 cps, rated at 2.5 volts output at 1000 cps for five selected inputs ranging from .0035 volts to .1 volts. Output impedance is 1500 ohms at 1000 cycles.

3. 1000 cycle low pass filter, General Radio type 830, 1500 ohm impedance at 1000 cps

4. Cathode-ray oscilloscope, Hickok Model 675-A, rated maximum sensitivity 20 millivolts rms/inch vertical deflection.

A block diagram of the final system arrangement indicating the relationship of the components is shown

in Figure III-1 below:

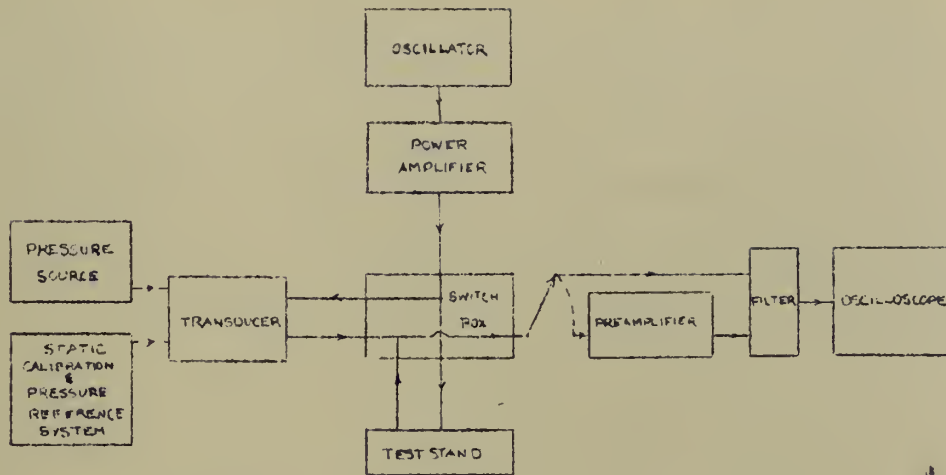


Figure III-1. Block diagram of final arrangement of components of the Schaevitz LVDT transducer system employed at the Webb Institute Towing Tank.

In order to present a complete analysis of the consolidation of these components into this final system arrangement, this section will include a detailed account of the design process followed plus calculations and component descriptions.

After the selection of the modified Schaevitz transducer, model P476-A10 utilizing a Schaevitz LVDT type 060SSL, considerable time lag was expected before delivery of the transducer. Rather than to wait for the arrival of the transducer to begin component selection, a test stand using a type 060SSL LVDT and a barrel micrometer head accurate to one ten-thousandth inch was constructed in order to have a means of simulating voltage and impedance characteristics of the

transducer input and output (See Figure II-11.). It is with these input and output characteristics in mind that most electronics instrumentation is designed. The design or selection of the power supply, on the other hand, is based upon the impedance characteristics and upon the voltage and frequency requirements of the load, in our case the transformer. It would have been possible, of course, to proceed with both the power supply and instrumentation selection with just the manufacturer's data and calculated values of voltage and impedance; however, with the data and calculations plus the actual simulated values of voltage and impedance, a more realistic and positive selection of each system component can be made.

The expected range of transducer output voltage was 2 mv to 730 mv for a pressure input of zero to ten inches water as derived from the rated sensitivity of 4.25 mv output per mil deflection volt input based upon a 400 cycle input and a 500,000 ohm load impedance.³¹ Since 6.3 volts input was recommended by the manufacturer and since .0274 inches of core deflection is equivalent to a pressure of 10 inches water (based upon the deflection of the Bristol pressure capsule, A1332-1, used as the pressure element of the selected transducer),³² the value of .73 volts was obtained:

$$27.4 \text{ mls} \times 63 \text{ v input} \times \frac{4.25 \text{ m.v}}{(\text{mil})(\text{v input})} = 730 \text{ mv}$$

The lower value of 2 mv was the order of magnitude of the null voltage (with null reducing circuitry at the transformer output) indicated by the data sheets supplied with the transformers used in the test stand. It must be noted that changing the input frequency or load impedance can result in changes in rated sensitivity. (A frequency of 1000 cps was used later which increased the sensitivity by about 6%.) The expected increment of transducer output voltage for an increment of pressure of .02 inches water, the desired resolution, was 1.47 mv:

$$.02 \text{ in H}_2\text{O} \times \frac{.0274 \text{ in deflec.}}{10 \text{ in H}_2\text{O}} \times \frac{4.25 \text{ mv}}{(.001 \text{ in deflec})(\text{v input})} \times 63 \text{ v input} = 1.47 \text{ mv}$$

Again, this calculation is based upon 400 cps input frequency and 500,000 ohm load impedance.

The voltage output of the test stand was made to simulate both the range and various increments of the transducer output voltage (neglecting errors in physical alignment of the test stand LVDT core plus manufacturing differences in the supposedly identical test stand and transducer transformers). This was accomplished by simply adjusting the micrometer of the test stand. The adjustment axially advanced the center shaft

of the micrometer to which was attached the core of the LVDT. Thus, as the micrometer was adjusted, the core of the test stand transformer was axially positioned just as the core of the transducer LVDT was positioned by a deflection of the pressure capsule. Henceforth, any axial core motion of the test stand or transducer transformers will be called "deflection."

The output impedance exhibited by the test stand LVDT would, of course, be the same as that of the transducer LVDT since they are identical. For a frequency of 400 cps the output impedance of the transformer was 1110 ohms. This impedance was a function of frequency only over the linear range (of 0 to 60 mils deflection in either direction corresponding to 0 to 1.6 volts output) of the LVDT's since the total secondary coil inductance was a fairly constant .314 henries over this linear range.

Upon the completion of the preliminary test stand trials, the selection of a readout or indicating component was begun. This component would have had to measure in some manner the output voltage of the test stand LVDT and eventually the transducer LVDT. Such a measuring device, however, would present a load impedance to the LVDT. A high load impedance results in a low current in the transformer output circuit that includes the two secondaries and the indicator. This

low transformer output current results in a negligible voltage drop in the secondaries and consequently the transmission to the indicator of the full induced voltage. Small load impedances (of the same order of magnitude as the output impedance or below), on the other hand, result in a significant current in the output circuit and voltage drop in the secondaries with a reduction of transformer output voltage.³³ Readout devices such as the cathode-ray oscilloscope (CRO) and vacuum tube voltmeter (VTVM) present load impedances of 500,000 ohms or more; thus they could be considered as prospective indicating components. A CRO and VTVM were both available for use in our trial instrumentation arrangements; the latter, however, proved to be extremely unreliable and unstable at low voltages so attempts to use it in our instrumentation were discontinued at an early date. (The possibility of using VTVM's of other designs will be discussed later in this section.) The available CRO was a Hickok Model 675-A with a rated sensitivity of one inch vertical deflection of the sweep per 20 mv rms. This means that a sine wave with a voltage of 20 mv will indicate a peak to peak vertical deflection of one inch. On the screen of this CRO there are 10 units per inch on the vertical scale; therefore the

$$\text{Sensitivity} = \frac{10 \text{ units/inch}}{20 \text{ mv/inch}} = .5 \text{ units/m.v.}$$

This rated sensitivity was found to be slightly in error. On the "X1 scale" and at the highest "Sensitivity" setting a maximum sensitivity of .455 units per mv was obtained. Thus to resolve a pressure of .02 inches water, it would be necessary to read the CRO presentation to an accuracy of

$$\frac{1.47 \text{ mv} / .02 \text{ in. H}_2\text{O}}{2.2 \text{ mv/unit}} = .64 \text{ units (peak-to-peak) / .02 in. H}_2\text{O}$$

This requirement at first seemed to be unreasonable since the optimum method of reading the CRO employs the change in amplitude of the wave form from a fixed reference rather than the peak to peak change - thus halving the .64 units which the operator would have to resolve on the scope to .32 units. (Subsequent experience, however, has shown that the amplitude of the waveform presented on the CRO can be read to the nearest .1 unit with a reasonably steady input.)

In addition to the CRO and VTVM, a number of conventional indicating instruments (voltmeters and ammeters) available at Webb Institute were considered and tried, all with unsatisfactory results accountable to insensitvity. Conventional instruments, in addition, generally present a load impedance considerably lower than that for either the CRO or VTVM.

Proceeding with the CRO, the test stand and the input voltage supplied by the forementioned Eico os-

cillator, an attempt was made to evaluate the apparent problem of reading the CRO to an accuracy of .32 units with the possibility in mind of having to purchase an amplifier for the transducer output for easier reading of the CRO. Here we ran into problems as the oscillator (output impedance 1000 ohms) and the transformer (input impedance 112 ohms at 400 cps) were not properly matched for maximum power transfer and the maximum rated power output of the oscillator was .1 watt. When loaded by the transducer, therefore, the voltage in the primary dropped from a desired 6.3 volts to about 1 volt resulting in a reduction of LVDT sensitivity by a factor of 1.0/6.3 or about .16.

Further work on testing the sensitivity of the LVDT in the test stand was accomplished at the David Taylor Model Basin using a Hewlett-Packard audio oscillator model 201B. It was found, for instance, that while the vertical scale had a total of 50 units, only the middle 26 units could have been used on account of possible parallax and tube curvature. At the maximum CRO sensitivity settings the useful range for pressure measurement was found to be

$$\frac{26 \text{ units}}{.32 \text{ units} / .02 \text{ in H}_2\text{O}} = 162 \text{ in H}_2\text{O range on the "X1 Scale"}$$

Early in Section II of this paper was discussed

briefly the ratio of useful range to resolution. For the Hickok CRO at any setting this range-resolution ratio would be

$$\frac{26 \text{ units useful range}}{.1 \text{ unit resolution}} = 260$$

It appeared, therefore, that if we were to have used an amplifier for increased sensitivity, we would have had to sacrifice useful range.

Anticipating the need for transducer output amplification, a number of attempts were made last autumn at Webb Institute to find and rehabilitate or to construct amplifiers suitable for our transformer output. The first amplifier tried was a Brush model OA-1. We modified this amplifier by placing an output transformer in the plate circuit of the last stage of the amplifier and by modifying the input and output connections and wiring to accommodate the LVDT and CRO leads. This amplifier proved to be unstable and the output waveform a badly distorted sine wave. A try at troubleshooting to correct the output signal proved unsuccessful, although it was deduced that defective filter capacitors could have been a possible cause of the difficulty.

Rather than spend additional time trying to correct the output signal of the Brush amplifier with no certainty of satisfactory results, a Kirby oscilloscope preamplifier, model SA-103, was assembled and tested.

The preamplifier was rated at zero to 100 amplification with an input impedance of 222,000 ohms, a maximum input voltage of .3 volts, and a maximum output voltage of 30 volts. The amount of amplification was found to be more than ample, but again the output was distorted by 60 cycle voltages rendering it virtually useless. Considerable time was spent by the authors attempting to correct the output, particularly with regard to modifying the shielding and grounding arrangements, but with no positive results. No further consideration of either amplifier was made.

It was after their unsuccessful attempts of rehabilitating the two amplifiers at Webb Institute that the authors commenced their ten week winter work period at the David Taylor model basin. During this period the transducer was delivered and component selection continued with the very valuable aid of DTMB facilities and personnel.

In order to check the performance specifications of the transducer a rough calibration of the transducer was conducted using an extremely accurate (to within .001 psi or .0277 inches water) mercury barometer which readily converted into a variable air pressure source by the McLeod Gage principle.³⁴ This pressure source, always below atmospheric pressure, was connected to the outside of the pressure capsule of our transducer where-

as the inside of the capsule was open to the atmosphere. The power supply was the forementioned Hewlett-Packard audio oscillator rated at 20 watts with .2% harmonic distortion at 1000 cps. (See figure III-2.)

The pressure output readings obtained in this first test were obtained by the so-called "null balance" method. In order to utilize this method, the outputs of the transducer and test stand LVDT's were connected to each other in the same manner that the ends of each of the secondaries of an LVDT are connected. For each core position of the transducer LVDT there would be a corresponding position of the test stand LVDT core that would effect the presence of null voltage. For each diaphragm deflection, therefore, there would be a corresponding micrometer reading at system null voltage.

This method was used during the entire stay of the authors at DTMB. The results were quite consistent but on account of the low deflections of both cores involved, the difficulty of reading the micrometer to an accuracy of less than .1 mil, and of finding the exact null, this method was considered quite tedious and was discarded upon the authors' return to Webb Institute.

During the early stages of our work at DTMB, several facts became quite apparent:

1. The use of a filter was needed in order to remove the harmonics apparently causing the distor-

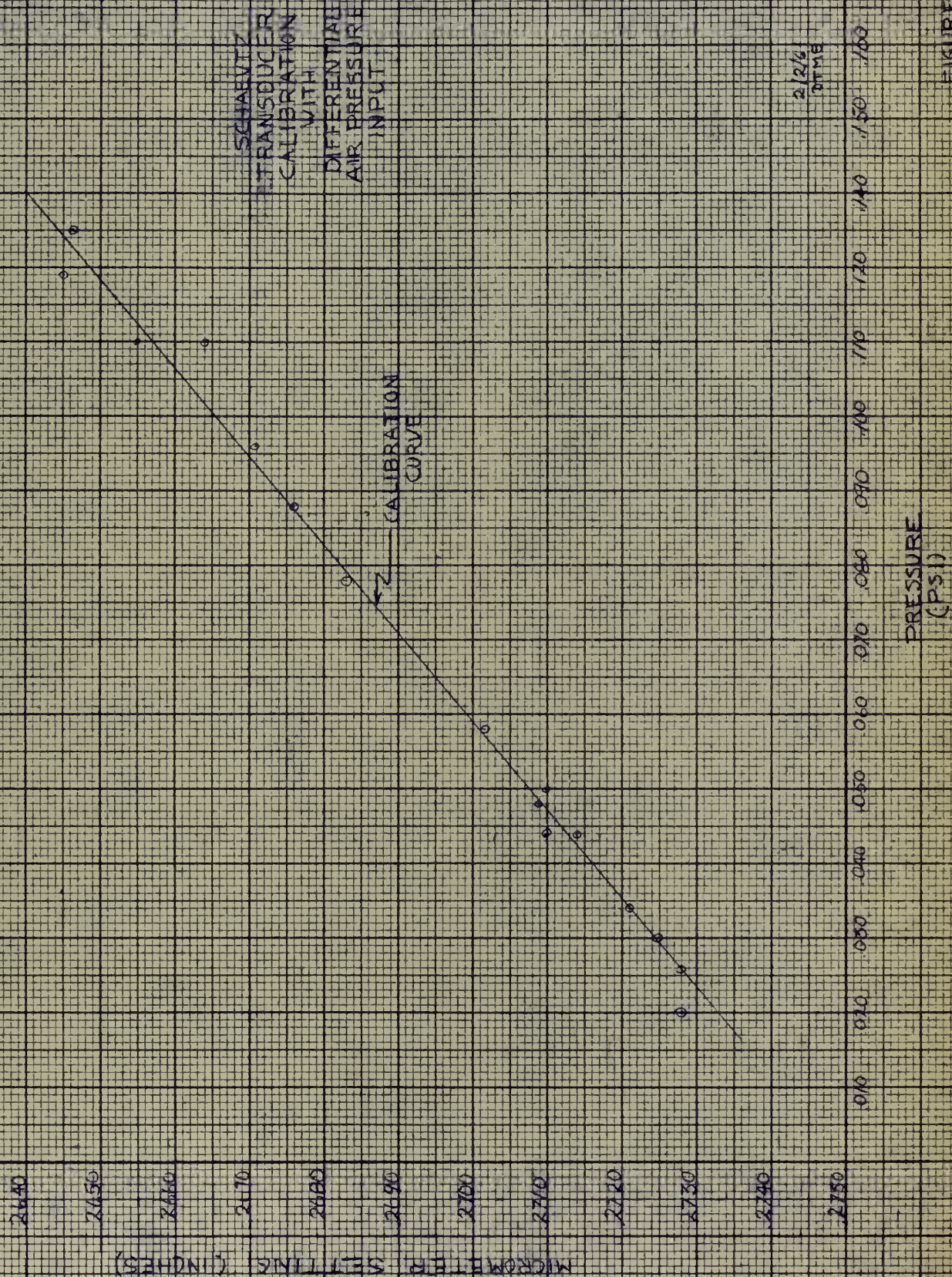


FIGURE 2

tion of the CRO waveform and the high frequency stray voltages affecting the stability of the waveform.

2. A power supply with sufficient power output to provide a stable, undistorted voltage of at least 6.3 volts to the transducer was needed.

3. A means of reducing the high null voltage found during the calibration would have to be employed. The null voltage without the presence of null reducing provisions was at least 20 CRO units in amplitude. This high null voltage, of course, restricted the useable portion of the most sensitive scale on the CRO and made difficult the establishment of any well defined reference core position.

4. The need for shielded leads throughout the external wiring was indicated in order to reduce the apparent stray or atmospheric voltage pickup.

Rather than actually constructing a filter network, several audio frequency filters available at DTMB were tried in conjunction with the transducer and the CRO. A General Radio, type 830, 1000 cycle low pass filter was found to be very effective in eliminating all detectable distortion. Also the stray voltage effects seemed to be considerably reduced. Furthermore, complete shielding of all external wiring essentially stopped most of the stray voltage pickup. This filter, therefore, was selected as a component of the final system and its effects on the system were as follows:

1. It limited the system working frequency to 1000 cycles per second.
2. It passed relatively undisturbed a 1000 cps voltage output of the transducer or test stand.
3. All voltages at frequencies below 1000 cps were also passed but at reduced amplitudes. For

example, a 50% reduction in amplitude at 300 cycles was realized.

4. voltages at frequencies above 1000 cycles were sharply cut off. There was a 83% reduction in amplitude at 1200 cps.

A 10,000 ohm Helipot potentiometer was connected across the output of the test stand LVDT or the transducer LVDT in order to reduce the null voltage. When used in conjunction with the General Radio filter, this potentiometer with careful adjustment proved to be capable of reducing the null voltage to less than one millivolt. In the final system this potentiometer was mounted in the switch box so that it could be connected across the output of either the transducer or the test stand.

The opportunity to use the small towing tank at the East End Hydrodynamics Laboratory at DTMB provided the chance to test the transducer under actual operating conditions using a Pitot tube as a pressure source. It was during these familiarization tests that the authors borrowed a Ballantine Model 300 VTVM in order to compare it to the CRO in its use as a readout component. Subsequent tests using the VTVM as the readout component for the transducer under actual operating conditions indicated that the VTVM was at least as sensitive as the CRO but not as flexible. This lack of flexibility manifests itself by the following:

1. The range to resolution ratio of the VTVM is low

considerably less than that for the CRO, generally about 100 when compared with the 260 figure pertaining to the Hickok CRO.

2. Both the range and sensitivity of each scale of a vTVM were fixed while those on the CRO were easily varied by the operator.

Because of the lack of flexibility of the VTVM and because of the availability as well as the performance of the CRO, the CRO was selected at the readout component of the transducer system.

The rejection of the vTVM was not meant to be construed that all vTVM's would not match the CRO in flexibility; but in general, VTVM's with the Ballantine model 300 as an example, would not do so.

Although the problem of obtaining a power supply capable of providing at least 6.3 volts to the transducer was temporarily solved with the borrowed Hewlett-Packard audio oscillator, it was necessary to buy or to construct a replacement for permanent use at Webb Institute. After a lengthy study of various manufacturers' catalogs, it was decided that a Heathkit power amplifier model UA-2 rated at 14 watts with its input voltage supplied by the fore-mentioned low powered Eico oscillator might satisfactorily provide the desired input to the system. This decision was based on the following circumstances:

1. The availability at Webb Institute of the Eico oscillator
2. The relatively low cost of the Heathkit power amplifier, about \$30.00, as compared to a \$700 plus

figure for the Hewlett-Packard oscillator.

3. A flat frequency response from 20-20,000 cps provided flexibility if the system frequency of 1000 cycle frequency (set by the choice of filter) was to be changed.

4. A rated harmonic distortion of less than .25% at 14 watts output reduced to .1% at less than 6 watts.

5. The power rating of 14 watts would provide for additional transducers in the system since the power required for one transducer of this type is

$$\frac{E^2}{R} = \frac{(6.3)^2}{58} = .68 \text{ Watts}$$

This Heathkit power amplifier was assembled from the manufacturer's kit using their recommended procedures with no modifications.. The output voltage of the Eico oscillator was connected directly to the input jack of the power amplifier. This combination of oscillator and amplifier easily provided the required 6.3 volts and proved to be extremely stable both in output voltage and frequency.

With the incorporation of sufficient power, proper filtering and shielding, and the potentiometer into the system with the CRO, it became increasingly clear, while making familiarization tests at DTMB, that the primary limitation on the pressure resolution of the system was the operator's ability to read accurately the CRO. Other possible limiting factors were:

1. Vibrations in the pressure pickup, such as the Pitot tube,

2. Vibrations in the transducer mounting, especially those from the towing carriage,
3. Speed control of the towing carriage, and
4. Pressure fluctuations at the source (Pitot tube, model hull or cylinder, etc).

This primary limitation again brought up the consideration of amplifying the transducer output voltage; for, as previously discussed, with amplification the number of CRO units change per change of pressure will be increased by the factor of amplification. This, of course, eases any problem of reading the CRO but decreases the full scale range. In order to be flexible in the number of CRO units change per change of pressure and thus provide a solution to possible problems of reading the CRO, the decision was made to construct or purchase an amplifier to handle the transducer output.

With the aid of previous experience with the Brush and Kirby amplifiers plus the manufacturers' catalogs, a Heathkit preamplifier model AA60 was selected. This selection was based on the following considerations:

1. A similar Heathkit preamplifier was borrowed and tested in the system with satisfactory results.
2. The preamplifier was immediately available at the reasonable price of around \$35.00.
3. As with the amplifier used in the power supply, the frequency response was flat from 20-20,000 cps thus providing flexibility in frequency selection.
4. Six input channels with a wide variety of input sensitivities and impedances were available in this one preamplifier.

5. Amplification factors from 0-200 were possible.
6. Total harmonic distortion was rated at .2%.
7. The noise and hum were low.

This amplifier was assembled using the manufacturer's recommended procedure with no modifications. Testing the completed amplifier in the system under actual operating conditions of the transducer showed the following:

1. The output was reasonably stable.
2. There was no distortion of the 1000 cps waveform.
3. A slight amount of stray voltage pickup was apparent on the peaks of the wave form but it did not hinder measurements.
4. A high degree of flexibility was possible by setting up various degrees of amplification on each of the input channels. The "crystal phono," "microphone," and "magnetic phono" inputs were utilized for X2.5, X5 and X10 amplifications respectively.
5. The output was linear if care was taken to prevent overdriving, i.e., excessive voltage inputs for the particular amplification. A calibration performed for each channel showed a gradual dropping off of the curve starting at a pressure of several inches of water. Use of lower amplification extended the range of linear outputs.

In order to provide a flexible means of tying together these various components with a minimum of external wiring, and to provide a chassis for the null reduction potentiometer, a switch box was constructed and wired.

Section IV - Development of Operating Procedures

To determine the optimum method of operating the transducer system several electronic arrangements or modes of the transducer and test stand LVDT were considered. There were three modes of operation tested by the authors for possible continued use. These were

1. Transducer mode
2. Differential mode
3. Bridge mode

Using the first two modes, tests were conducted using calibrated static and known Pitot tube dynamic heads. Before proceeding further with the discussion of the various modes of operation, descriptions of the assemblies used to obtain these pressures plus the method of mounting the transducers are necessary to properly describe the transducer operations.

The transducer itself was securely bolted to a small plywood table which in turn was secured to a mounting board, hereafter referred to as "the board." On the board was placed a U-tube water manometer, a bellows, a small electrical terminal box, a reservoir, connecting tubing, and associated fittings. If dynamic pressure inputs to the transducer were desired, the board was secured to the underside of the carriage, and a $\frac{1}{4}$ inch diameter Pitot tube was clamped to a

towing strut mounted forward of the board. For static calibrations the board was removed from the carriage and placed alongside the tank dock in a vertical position with the Pitot tube in a can of water alongside.

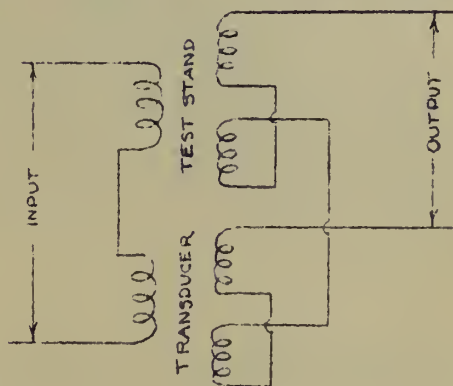
The transducer and tubing had to be filled with water and all the air removed before any pressure measurements could be taken. This was accomplished by a sucking process in which the water was drawn up through the Pitot tube static and dynamic openings, through the tubing into the transducer, and up through the vents. Once assured that no air remained in the transducer, tubing, or Pitot tube, the tubing attached to the transducer vents was securely clamped. During this sucking process it was necessary to tilt the transducer to various angles to insure that no significant amounts of air was trapped within. It is possible that the presence of air bubbles in the tubing or transducer may have caused nonlinearities in the output on a number of occasions. Every two or three days additional efforts were made to insure complete absence of air inside the transducer. In addition a small amount of detergent was placed in the liquid in the inside of the capsule to aid in air removal.

The transducer mode of operation was accomplished by applying the input voltage from the power supply to the primary of the transducer LVDT and connecting the



output to the CRO via the filter. The preamplifier could be placed in the system between the output of the transducer and the filter if desired. The change in amplitude of the wave form on the CRO was the measure of the pressure.

In the differential mode (or null balance mode of operation mentioned in Section III) of operation the input voltage, usually about 12.6 volts, was applied across the series connected primaries of both the transducer and test stand transformers. Their outputs were connected differentially (in series opposition) as shown in the figure to the right.



In this manner the output of the test stand transformer could be used

Schematic for connections in differential mode

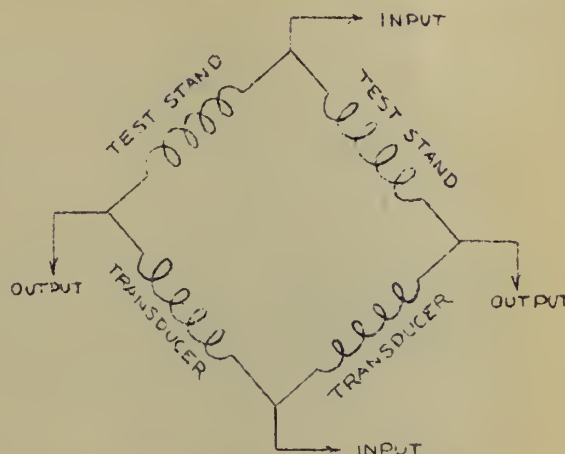
to balance out or null the output voltage of the transducer. For a given pressure input to the transducer, there would be a micrometer setting that would cause the system voltage to fall to zero. It was possible, therefore, to calibrate micrometer setting against pressure input.

In the bridge mode of operation, the primary coils of the transducer and test stand transformers were dis-



connected and the four secondaries were connected as an inductance bridge as shown in the figure to the right.

By this arrangement, pressure inputs to the transducer would unbalance the bridge previously balanced by the test stand micrometer. This unbalance



Schematic for connections in bridge mode

would have produced an output voltage that varied in some manner with pressure input. As before, this output voltage was connected to the CRO via the filter, and once more the use of the preamplifier was optional.

After a considerable number of trials, the transducer mode was determined to be the best way to operate our particular system with regard to both pressure resolution and ease of operation. The differential and bridge modes were given no further consideration after their initial tests for the following reasons:

Differential Mode - 1. Null balancing the transducer output with the test stand micrometer with dynamic pressure inputs to the transducer proved to be very slow and nearly impossible to accomplish before the end of the run at carriage speeds above four feet per second. This difficulty did not present any problems for static calibrations.

2. The system resolution was limited by one's ability to read the micrometer. The smallest increment of the

micrometer that can be read is .0001 inch which is equivalent to

$$.0001 \text{ in} \times \frac{4.25 \text{ mv}}{(.001 \text{ in})(V_{\text{input}})} = 2.84 \text{ mv output change}$$

In Section III it was determined that a pressure change of .02 inches water results in an output voltage change of 1.47 mv. This limits the resolution of this method to

$$\frac{2.84 \text{ mv}}{1.47 \text{ mv} / .02 \text{ in H}_2\text{O}} = .0386 \text{ in. H}_2\text{O}$$

It was possible, however, to interpolate indicator readings between indicator readings for adjacent integral micrometer settings for improved resolutions. This procedure was time consuming and somewhat tedious.

Bridge mode - 1. This mode was characterized by a low signal to noise ratio. The transducer output voltages were readily affected by stray voltage pickup and cable reactances causing unsteady, difficult to read waveforms on the CRO. This unsteadiness of the waveform precluded use of the mode with the CRO; use of this mode with the VTVM was not attempted.

2. The null point was extremely difficult to find.

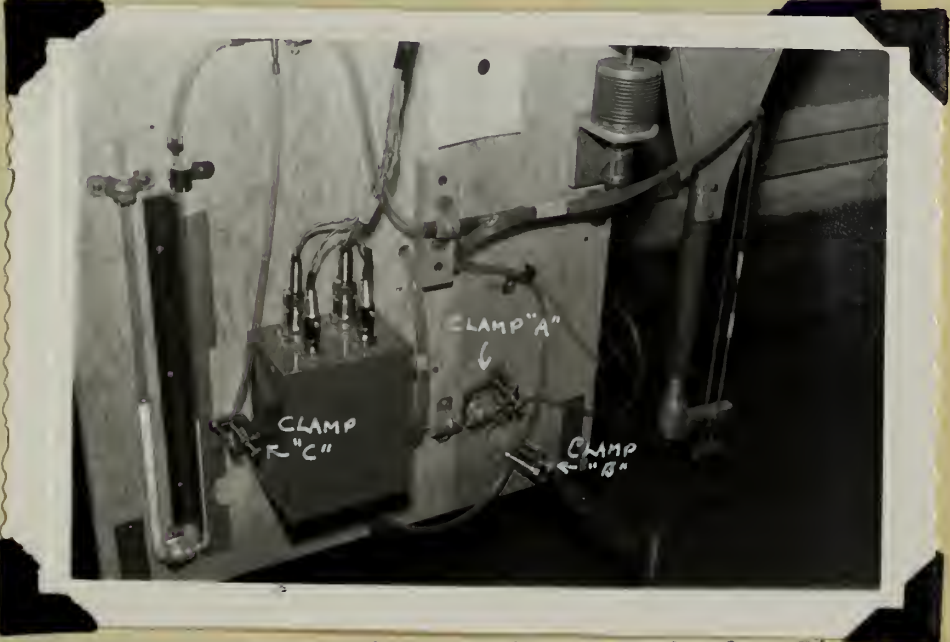
(Resolution trials indicated that sufficient sensitivity could be obtained by use of this mode consistent with our resolution requirement of .02 inches water.)

With the selection of the transducer mode of operation, the authors conducted a series of dynamic tests with the Pitot tube using no amplification to determine the actual performance of the transducer-filter-CRO combination. In carrying out these dynamic tests the following procedure was used:

1. The board and the Pitot tube (secured to the acceleration bar) were fastened under the carriage.

2. The static side of the Pitot tube was connected directly to the outside of the transducer pressure capsule. The dynamic side of the Pitot tube was

connected via a tee connection to the inside of the diaphragm and to the reference pressure assembly. The tubing to these static components was clamped off with clamp A. (The arrows on the photograph below points to clamps A, B and C.)



The "board" mounted on the carriage ready for Pitot tube tests. Arrows point to clamps A, B and C. On the upper right corner of the board is the bellows; at the far left are the manometer and the scale.

3. All electronic components were connected and energized at least one hour before use. This warm-up requirement also applies to the carriage drive and speed control systems. The tank skimming valve was also turned off at this time to ensure a constant water level.

4. All air was removed from the system using the vents on the transducer in the previously described manner.

5. With the CRO "Vert. Atten." knob set on "X1" and with maximum "Vert. Gain," the transformer position adjustment screw on the transducer (see photograph on next page) was adjusted to give a peak-to-peak value of about 5 units on the CRO. The exact initial amplitude of this sine wave was not critical; it simply serves as an initial reference. The "Horizontal Selector" knob of the CRO was then set on "X10 amp." to enable a vertical line to be read on the CRO face.





The rear of the "board." Lt. Sesler is pointing with the pencil to the transformer position adjustment screw, also known as the "zero-set," at the base of the transducer. Closer to the camera wrapped in masking tape is the reservoir.

6. The carriage was then run at various speeds to enable a series of velocity heads to be plotted against a change in amplitude of the CRO wave form (in this case a vertical line.) Note: This change that is noted is exactly half of the change of peak-to-peak amplitude.

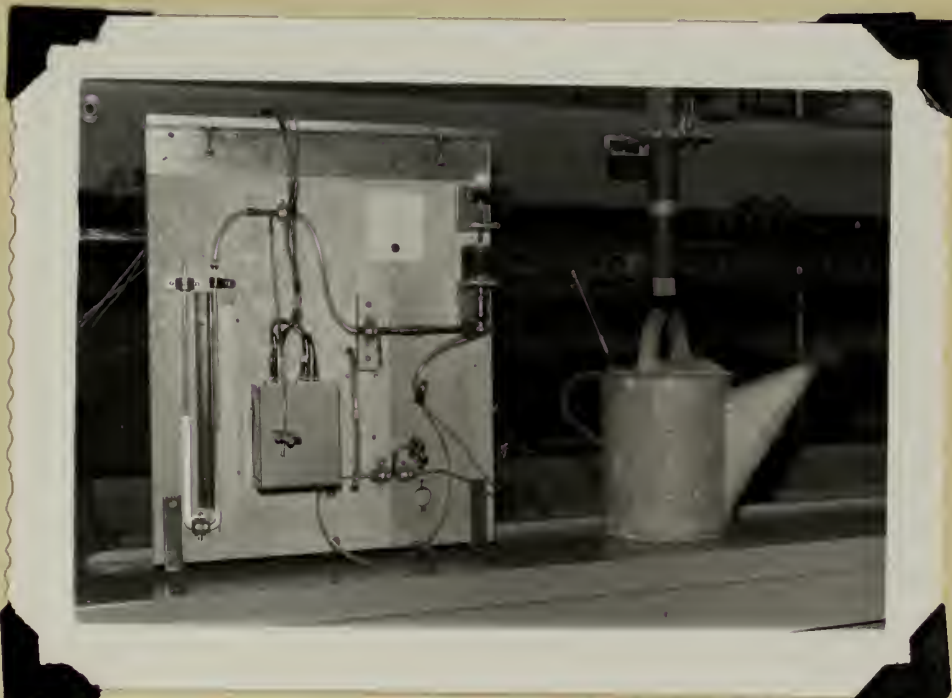
7. As soon as the velocity head was greater than necessary to change the amplitude of the wave form more than 26 units, a shift of the "vert. atten." knob to the 110 scale was necessary.

These dynamic tests indicated that this system with a velocity head input to the transducer from the Pitot tube produced nonlinear output readings. A deviation from a straight line calibration (as determined from later static calibrations) of as much as .15 inches water at the lower range of 0 to 1.5 inches water to as high as one inch water at velocity heads from 1.5 to ten inches water was noted. This

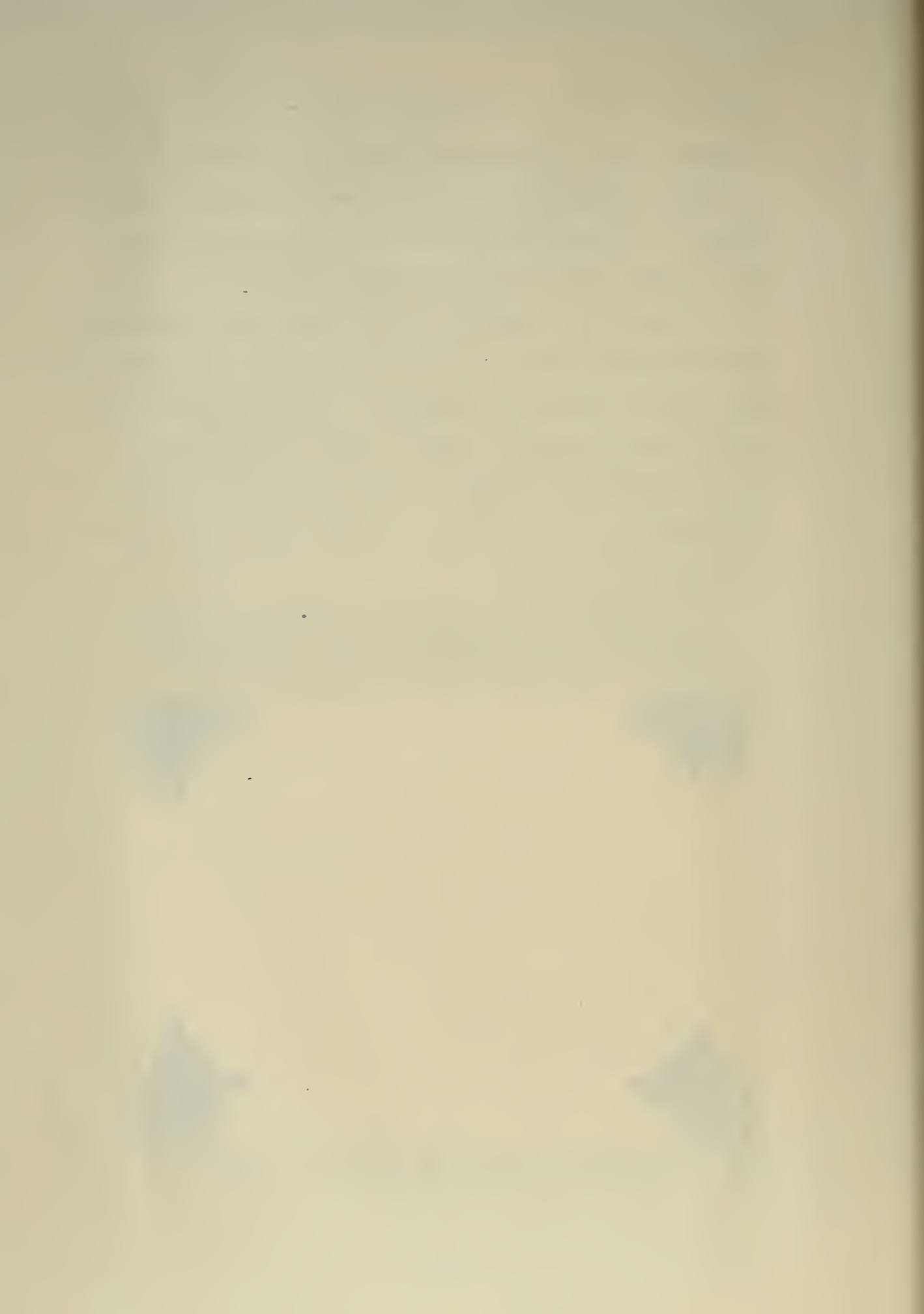
deviation varied in an "S" fashion about the best-fit straight line indicating the possible presence of resonant frequencies existing in some portion of the system. A discussion of this problem and of its partial solution follows later in the section.

In order to proceed with checking the performance of this system and to attempt to pinpoint the cause of the nonlinearity noted with dynamic inputs, a static calibration was conducted. At the same time various combinations of input voltage and amplification factors were tried. The procedure used for this static calibration was as follows:

1. The board was placed on the side of the dock with the Pitot tube immersed in a can of water alongside as illustrated in the photograph below.



The board placed on the side of the dock ready for static calibration of the transducer.



2. The static side of the Pitot tube was connected directly to the outside of the transducer pressure capsule. The dynamic side of the Pitot tube was isolated by tightly closing clamp B. The reference pressure assembly (bellows, reservoir and U-tube manometer) was connected via the fore-mentioned tee connection and clamp A opened.

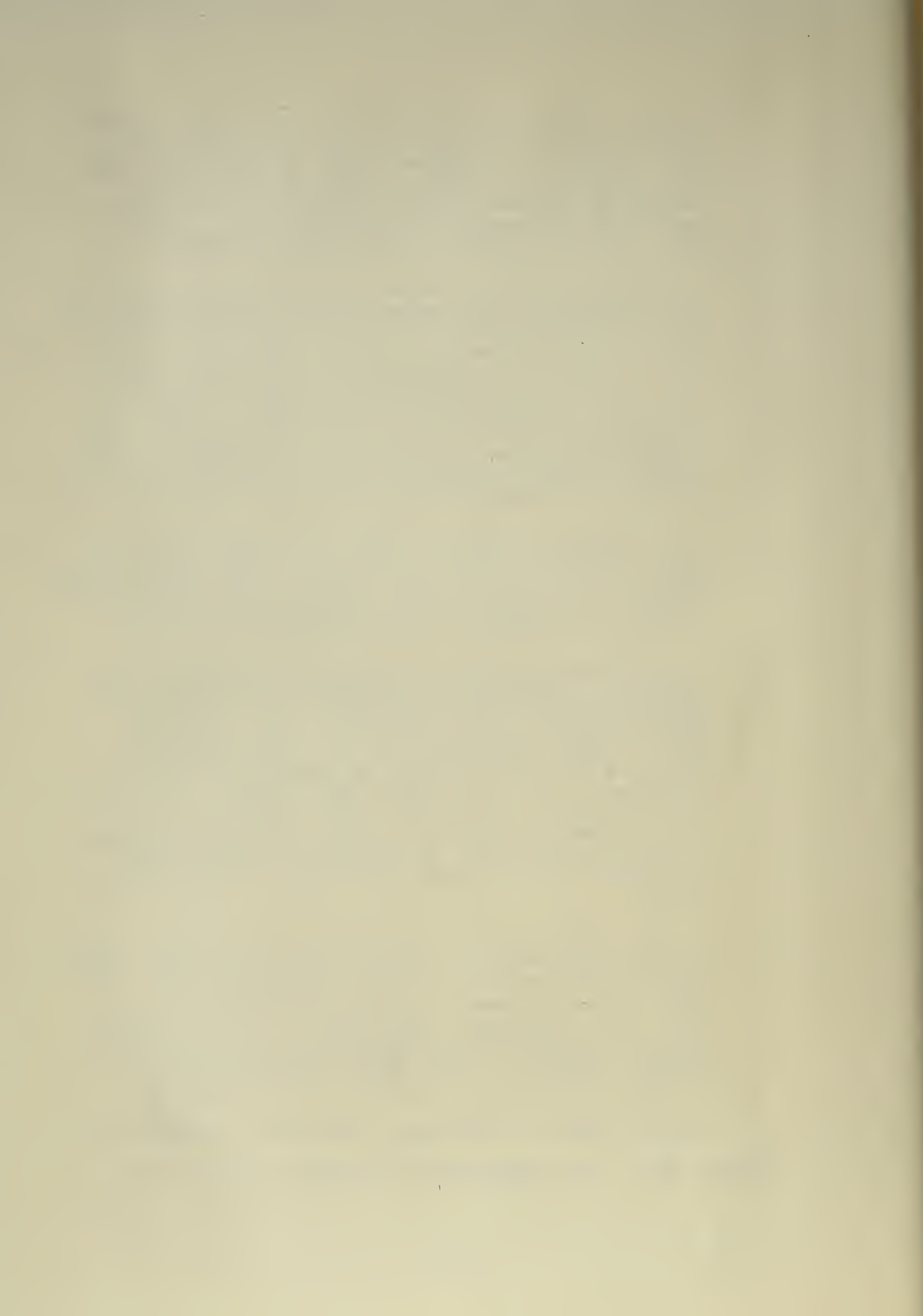
3. The reference pressure apparatus was then filled with water until the water level approached but had not yet reached the top of the reservoir (located on the same side of the board as the transducer.) This filling was accomplished by opening clamps A, B and C and by sucking up water through the Pitot tube being careful not to draw water up from the manometer toward the bellows. (The reservoir provides a large free surface thus preventing possible errors of static pressure due to expansions or contractions of the transducer pressure capsule.)

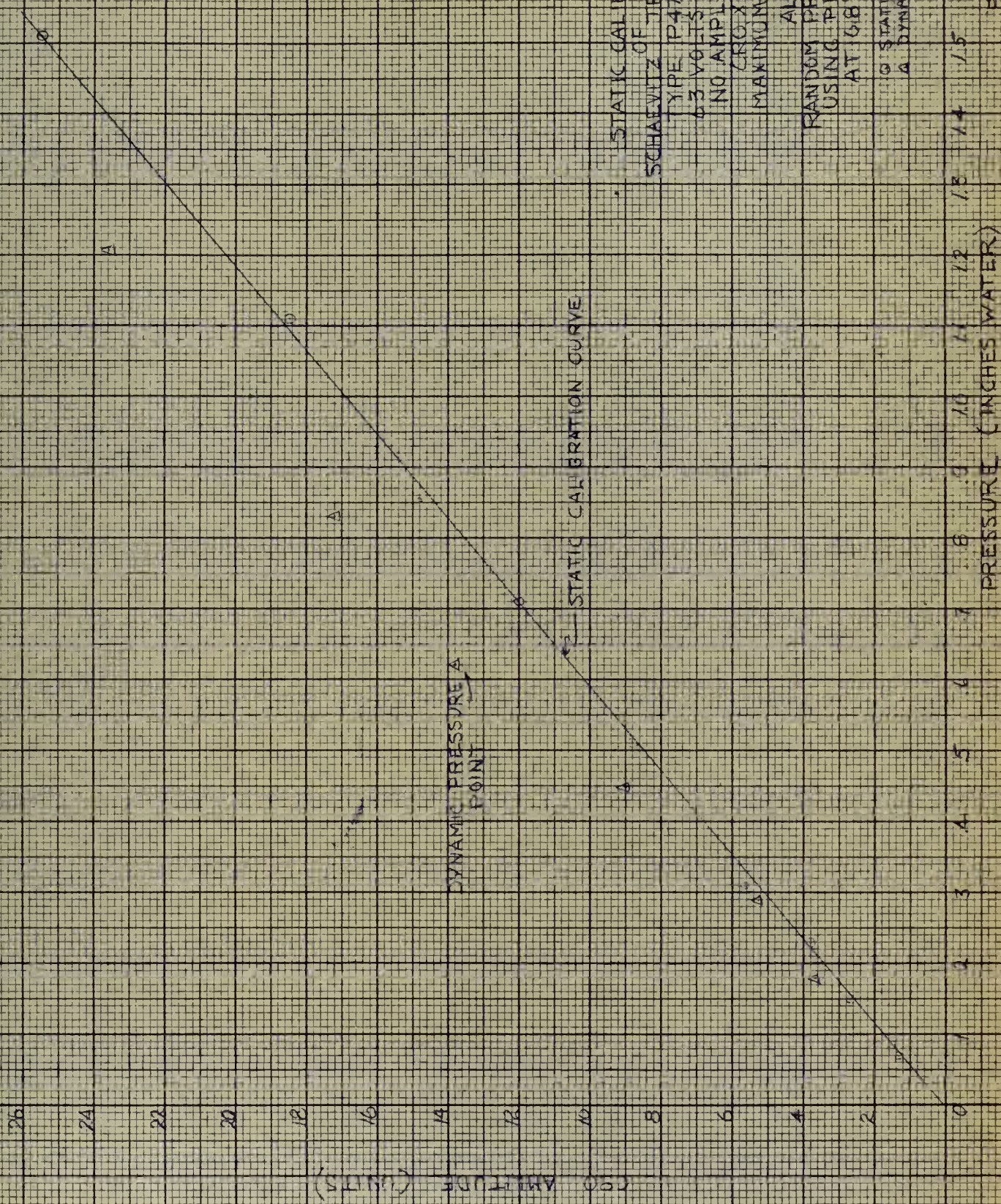
4. With the reservoir fluid at the desired level, clamp B closed, and clamps A and C open, the transducer output was nulled by means of the transformer position adjustment screw and the output then increased to a peak-to-peak height of five units.

5. Clamp C was then closed and the bellows compressed (for positive pressures) or expanded (for negative pressures) thus producing a change of water heights in the manometer. The change of water height on one side of the manometer was obtained by using a scale graduated in hundredths. An accuracy of .01 inches water height could be read. However, since the total height change in the U-tube was twice the change of height reading, a factor of two must be applied to the reading to obtain the pressure input change to the transducer.

6. The output voltage changes on the CRO were read in the same manner as used in the Pitot tube tests. Whenever it is noted (in any experiment) that the CRO amplitude shows a marked dip followed by a rise, the transducer transformer position adjustment screw should be readjusted to pass the transformer through the core null position until the 5 units peak-topeak reading is again obtained.

Sample static calibration curves are presented in Figure IV-1. The calibration curve for the 11 scale





STATIC CALIBRATION
 SCHAEVITZ OF TRANSDUCER
 TYPE IP476-A10
 63 VOLTS IN, 000V
 NO AMPLIFICATION
 CRO XI SCALE
 MAXIMUM SENSITIVITY
 ALSO
 RANDOM PRESSURES
 USING PITOT TUBE
 AT 68' DEPTH

10' STATIC
 A DYNAMIC
 10 15 16
 FIGURE III-14



ERO AMPLITUDE (UNITS)

DYNAMIC PRESSURE
POINT

STATIC CALIBRATION CURVE

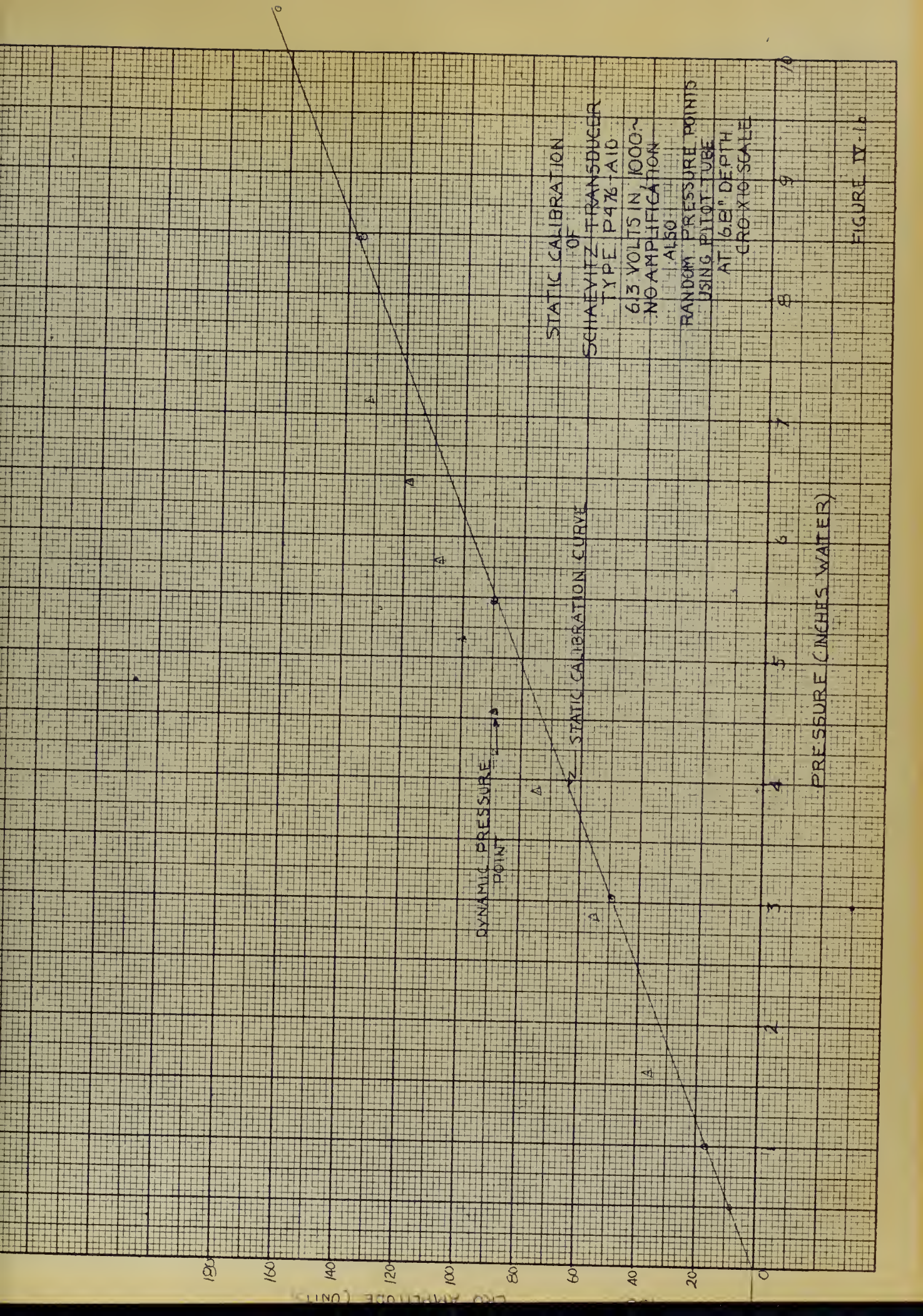
STATIC CALIBRATION
OF
SCHAEVITZ TRANSDUCER
TYPE P476-A10

6.3 VOLTS IN 1000~
NO AMPLIFICATION
ALSO

RANDOM PRESSURE POINTS
USING PILOT TUBE
AT 6.8" DEPTH
CRO X10 SCALE

PRESSURE (INCHES WATER)

FIGURE IV-16

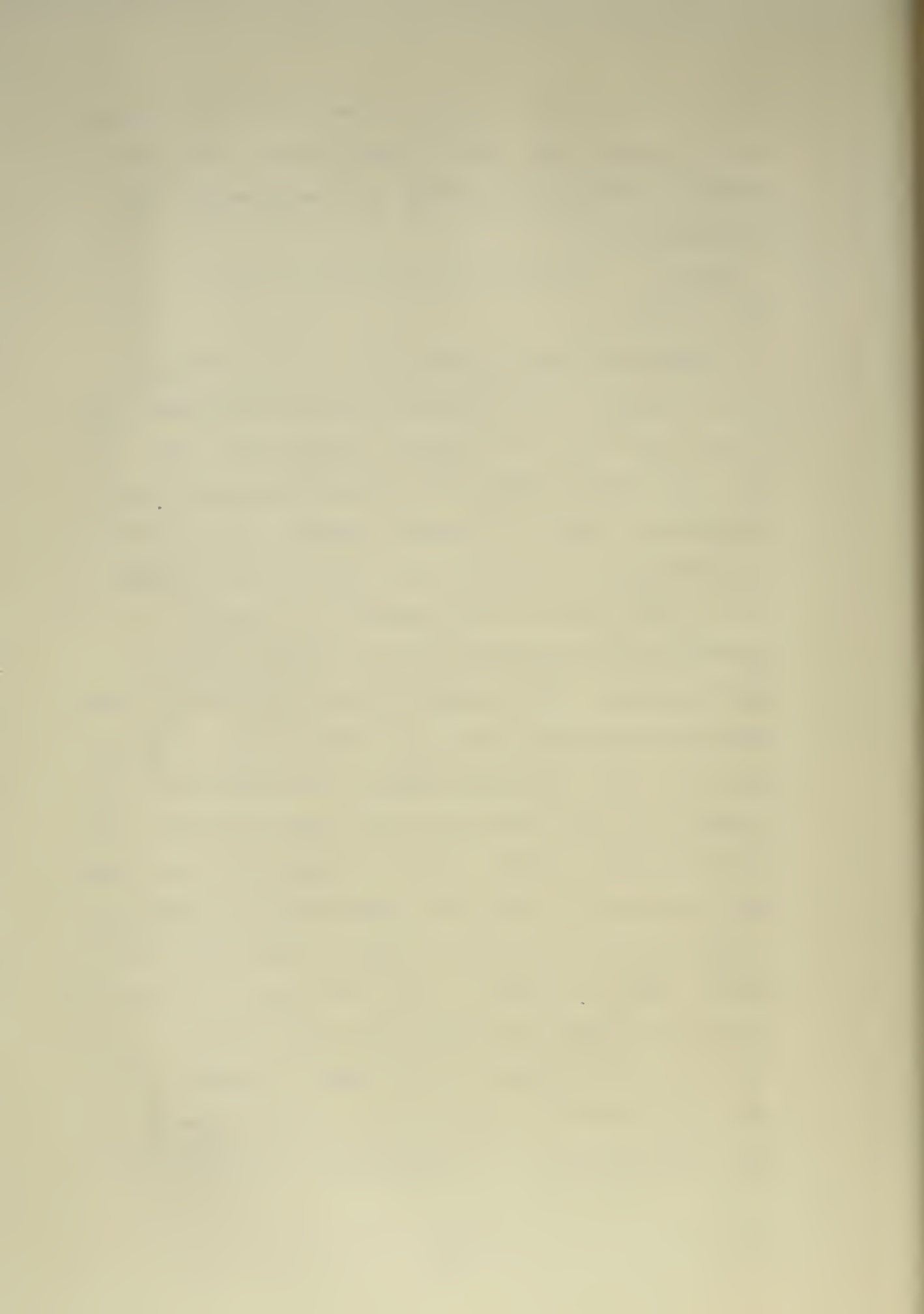


of the CRO indicated a system sensitivity of .33 units per .02 inches water with no amplification. With an ability to read to an accuracy of .1 unit on the CRO a resolution of

$$\frac{.1 \text{ unit}}{.33 \text{ units}} \times .02 \text{ inches water} = .006 \text{ inches water}$$

was possible.

These calibration curves also include information from the dynamic tests showing deviations from the best-fit straight line of the static calibrations. The fact that these sample curves from static calibrations were linear showed that the probable cause of non-linearities in the results of the Pitot tube tests were on account of the input pressure. This problem was further narrowed to probable vibrations in various planes of the Pitot tube. This lateral vibration effect was determined by clamping off the input from the Pitot tube dynamic side; the resulting pressure inputs from the static opening of the Pitot tube for a series of runs indicated amplitudes of from .2 to 2.0 units over a carriage speed range of 0 - 5 feet per second (the amplitude for a single speed was fairly constant). This output showed resonant peaks at about 1.7 feet per second, 2.9 feet per second and 3.9 feet per second with amplitudes of 2.1, 1.1, and .4 respectively. Decreasing the depth of the Pitot tube from 6.8 inches to 4.2 inches resulted in the lower peak shifting to a new resonance of approximately



the same amplitude at 2.2 feet per second. From this increase it was concluded that the lateral vibration producing an equivalent velocity head at the static openings was a probable explanation for the loss of linearity.

The static openings of the Pitot tube were then isolated by clamping the tube to the static side of the Pitot tube and by connecting the dynamic opening of the Pitot tube directly to the outside of the pressure capsule of the transducer. The inside of the pressure capsule was connected to the pressure reference assembly with clamp B closed and clamps A and C open. In this manner the inside of the pressure capsule was always open to a pressure that varies only with atmospheric pressure through the reservoir and open clamp C.

Using the above connections with the static openings of the Pitot tube isolated, the dynamic tests were re-run. As a further precaution the Pitot tube was raised even more to a new depth of 1.7 inches below the surface with the following results:

1. Deviations of readings in the 0 to 1 inches water range were effectively eliminated.
2. At higher pressures the maximum deviations were about .5 inches as compared to the original value of about one inch.

It was suspected that the remaining deviation was also due to vibrations or other deflections of the Pitot tube

under dynamic loading. This problem, however, was not pursued further due to time considerations.

Representative curves of pressure versus output voltage units using various input voltages and amplification factors are included as sample calibrations. (See Figures IV-2 and IV-3.)

Conclusions - A pressure transducer, Schaevitz type P476-A10, was determined to be the most suitable instrument for use with a four foot Webb Institute Towing Tank model. The system that was constructed was found to be capable of resolving better than the desired .02 inches water, and it appears, therefore, that the system should prove very useful for making pressure and boundary layer surveys.

Recommendations - 1. A Pitot tube of a rigid design is recommended for velocity surveys in conjunction with this transducer system to preclude significant vibrations and deflections under dynamic loading.

2. For pressure surveys around ship model hulls, the following connections on the transducer and on the board are suggested:

a. The tubing from the dynamic head of the Pitot tube should be connected directly to the outside of the transducer pressure capsule.

b. It may be desirable to have the board ready for periodic static calibrations. The tubing to the reverse face of the diaphragm should be open only to a volume of water that partially fills the reservoir. By opening clamp "C" (the water should be retained in the manometer) the surface of the water in the reservoir is ex-



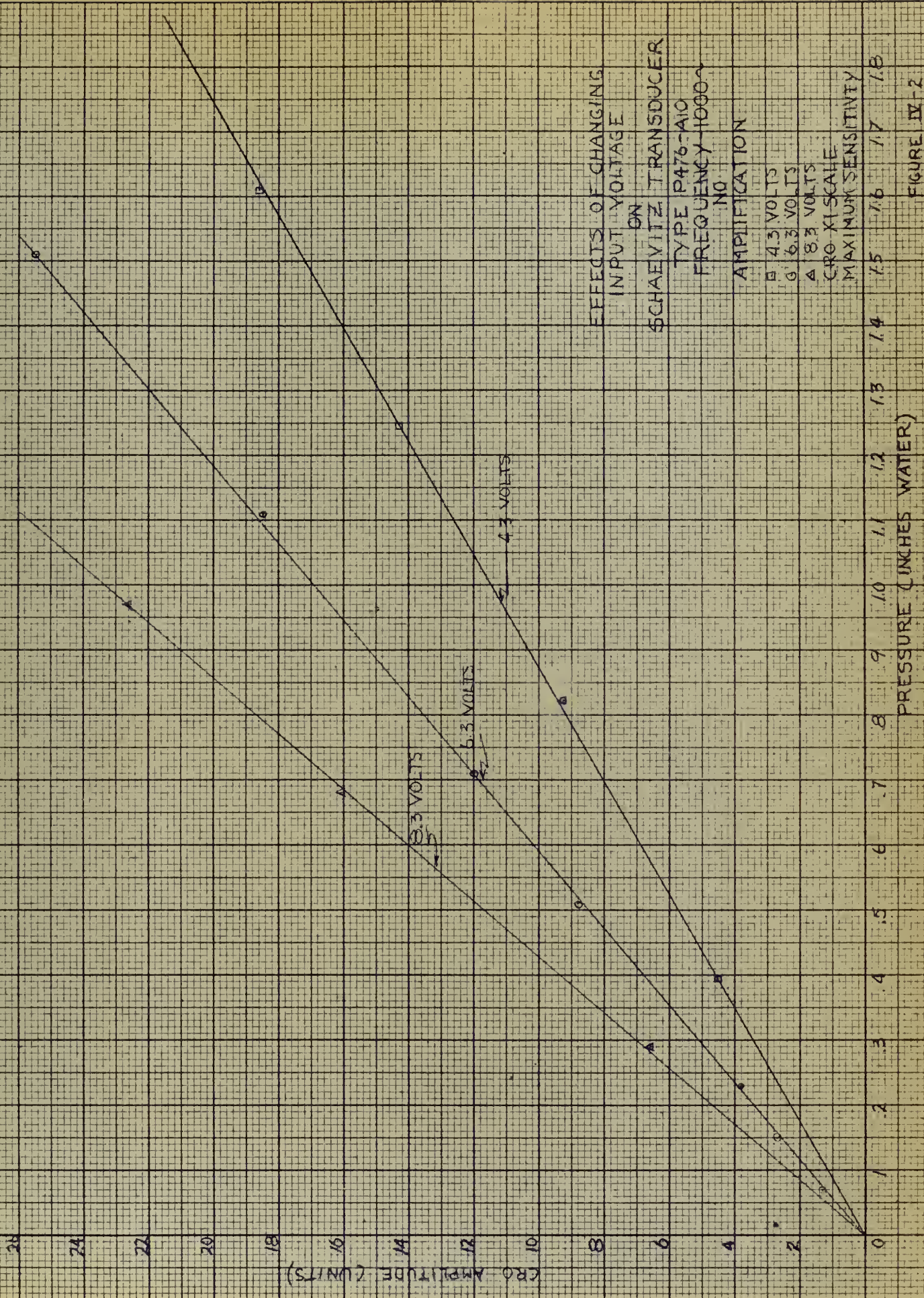
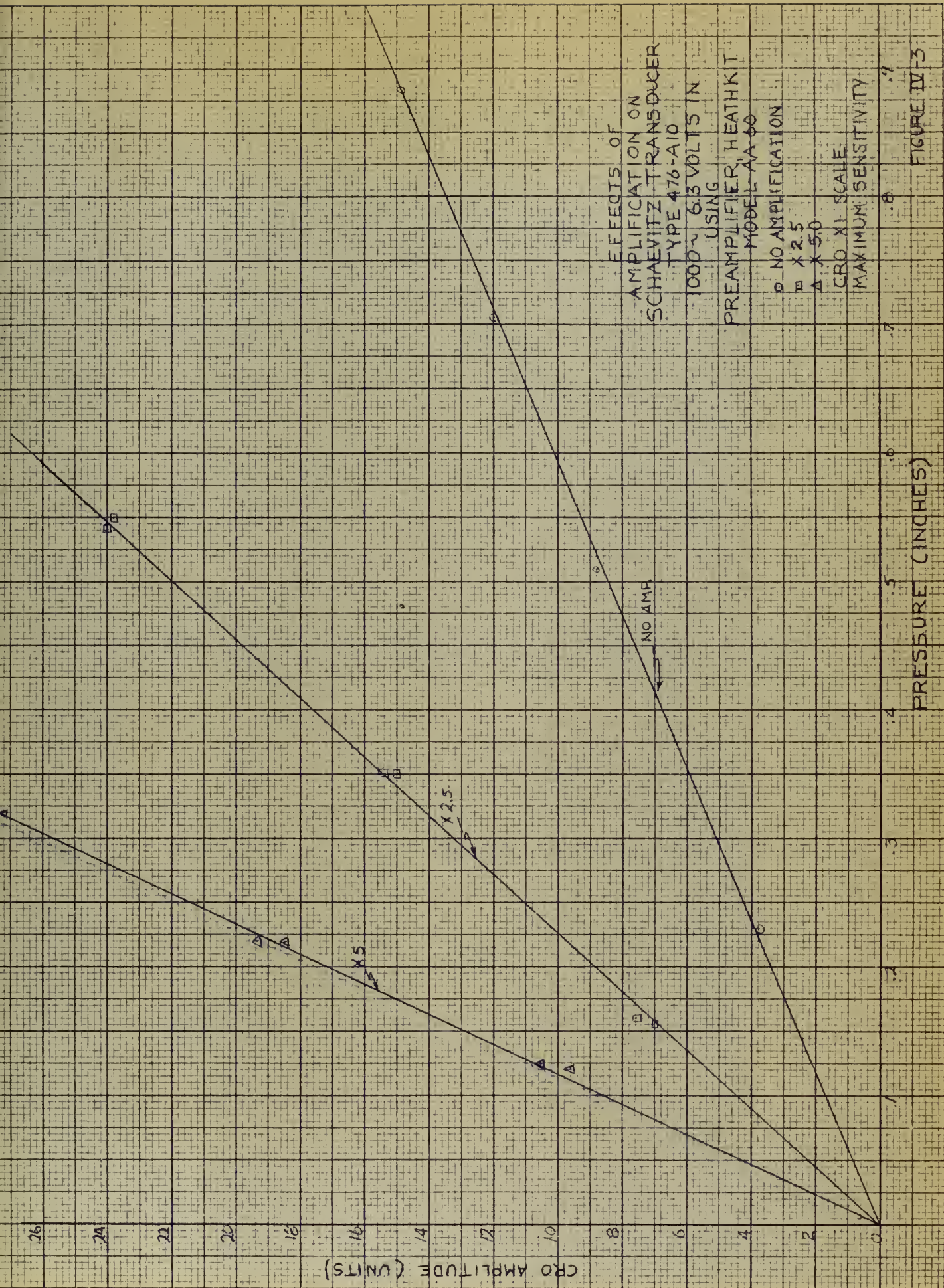


FIGURE IV-2





EFFECTS OF
AMPLIFICATION ON
SCHAEVITZ TRANSDUCER
TYPE 476-A10
1000 ~ 6.3 VOLTS IN
USING

PREAMPLIFIER, HEATHKIT
MODEL AA-60

□ NO AMPLIFICATION

■ x25

▲ x50

CRO XI SCALE

MAXIMUM SENSITIVITY

PRESSURE (INCHES)

FIGURE IV-3



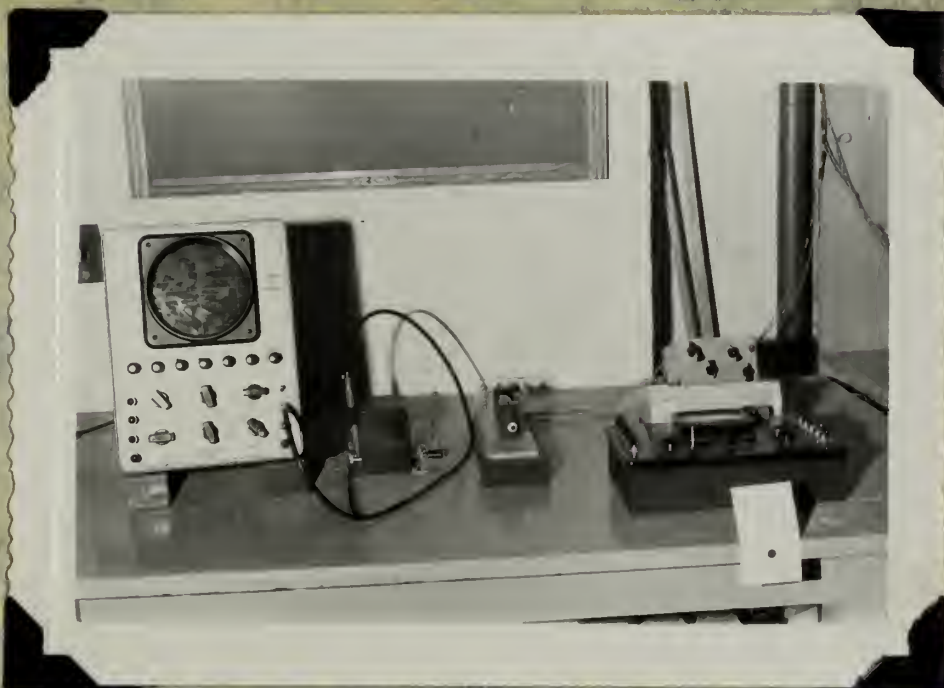
posed to the same atmospheric pressure changes as is the surface of the towing tank.

Connections made in this manner would enable one to conduct a static calibration check at any time by closing clamp "C" and by adjusting the bellows.

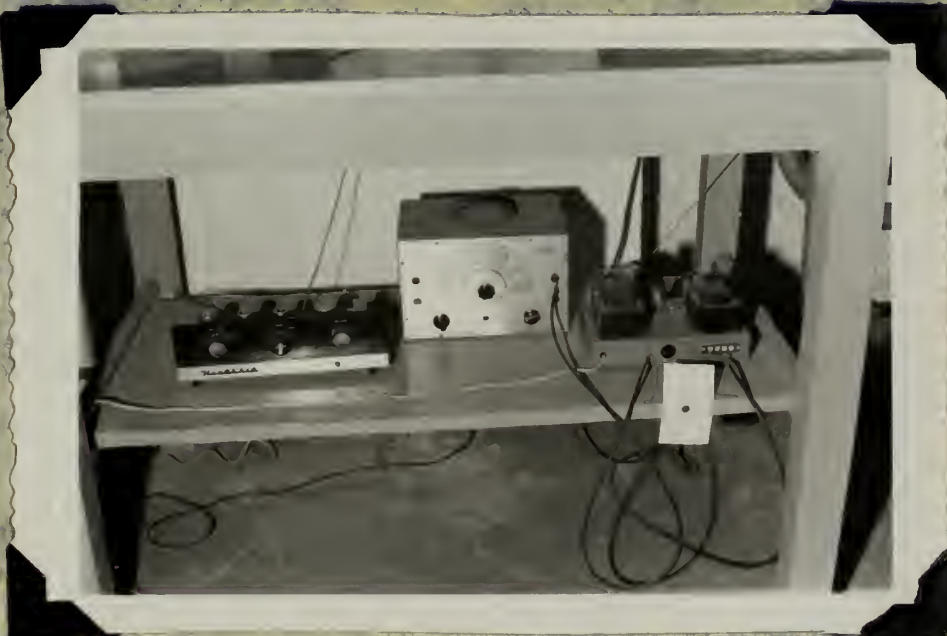
3. A method of effectively increasing the useful pressure range has been successfully devised. The transformer position adjustment screw should be adjusted so that the amplitude of the waveform is increased to a peak-to-peak height of up to 26 units (13 units above the horizontal sweep). This adjustment should be made in such a manner as to purposely effect a passing through of the null point by the transformer core, i.e., when the pressure (or suction) to be measured is applied, the CRO waveform would decrease to null and then rise again. The heights of the waveforms above the horizontal sweeps, before and after application of the pressure, are measured, added and diminished by one unit. (It now appears that the null voltage is about $\frac{1}{2}$ unit.) In view of the fact that linearity exists in the output on both sides of null, the calibration curve in use could be extended to the reading on the ordinate just obtained and the pressure determined thereby.



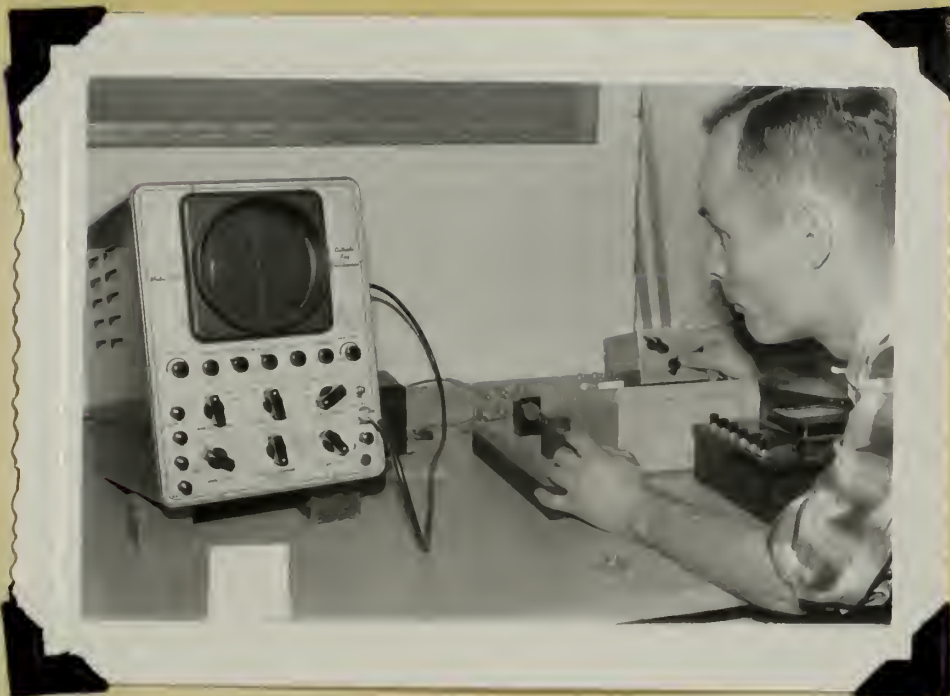
his own methods for the testing ranges.



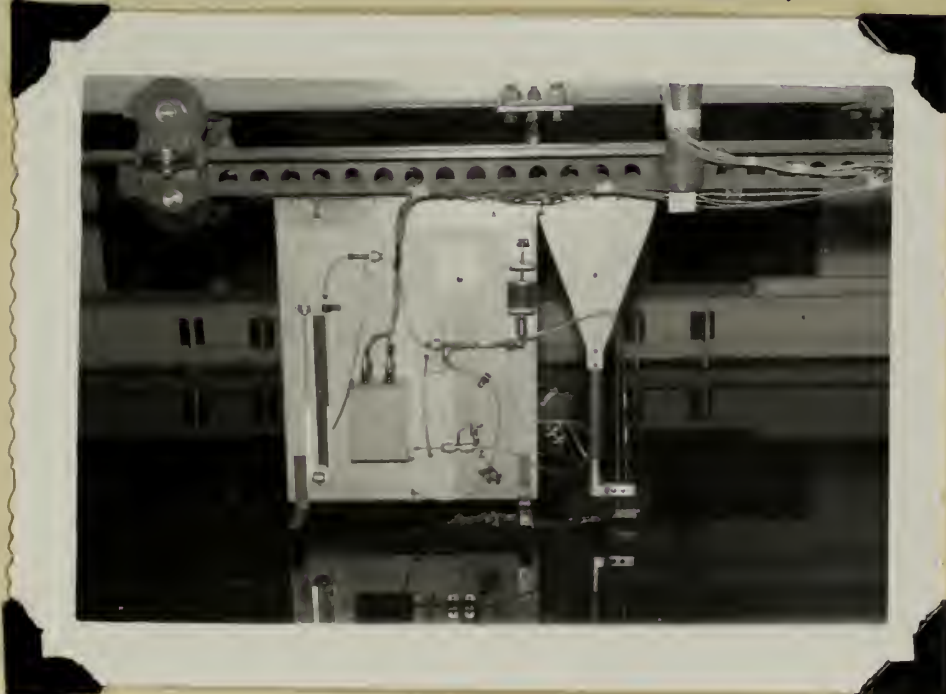
The instrumentation appearing on the table top are (left to right, front) the cathode-ray oscilloscope, filter, test stand, and voltmeter for determining power supply output voltage. Behind the voltmeter is the switch box.



The apparatus on the bottom shelf are (left to right) the preamplifier, the audio oscillator, and the power supply amplifier.



Lt. Christmas nulls the test stand transformer by adjusting the micrometer with his left hand and the null voltage reducing potentiometer with his right hand. (The CRO presentation does not appear on account of reflection from the flash bulb.)



A Pitot tube test is being conducted at five feet per second.



Footnotes

1. Hogben, N., "Ship Hull Pressure Measurements," Trans. Institution of Naval Architects, 99, p 446 (1957)
2. The lengths of runs used for Hogben's experiments were about 60 to 70 feet and two "booster" runs were generally required prior to the final run after which column heights were measured. Previous runs at nearly the same model speeds served as booster runs. ibid, p 452.
3. Perry, J. H., ed., Chemical Engineers' Handbook, Third Ed., McGraw-Hill Book Company, 1950, p 365.
4. The "apparent error" is regarded as the greatest divergence of readings that can be reasonably expected of plotted points from the best-fit curve obtained from these points during a calibration.
5. Hogben, op cit, p 451
6. Eggert, E. F., "Form Resistance Experiments," Trans. Soc. Naval Architects and marine Engineers, 43, p 140 (1935).
7. Eggert, E.F., "Further Form Resistance Experiments," Trans. Soc. Naval Architects and marine Engineers, 47, pp 308-315 (1939).
8. The usual number associated with vortex shedding frequencies from a cylinder is the Strouhal Number, nd/V where n is shedding frequency, sec^{-1}
 d is cylinder diameter, feet, and
 V is fluid velocity, feet per second.
 Based on previous work and studies accomplished by one of the authors on vortex shedding around cylinders, he learned that below a Reynold's Number of about 2×10^5 (the characteristic dimension for Reynold's Number being the cylinder diameter) the Strouhal number remains a fairly constant .192. Assuming this figure to be correct, the expected shedding frequency for a two inch diameter cylinder traveling seven feet per second through water in a direction normal to its axis would be

$$.192 = \frac{nd}{V} \quad \therefore n = \frac{.192V}{d} = \frac{.192(7)}{.1667} = 8.06 \approx 8 \text{ sec}^{-1}$$
9. The question of obtaining two transducers capable of handling water on one side of the diaphragm may be considered as an alternative to the procurement of one

transducer capable of handling net liquid pressures. This matter could be resolved, of course, by comparing the total costs of systems using transducers handling but one liquid and by considering the practicality of constructing instrumentation capable of indicating net liquid pressure.

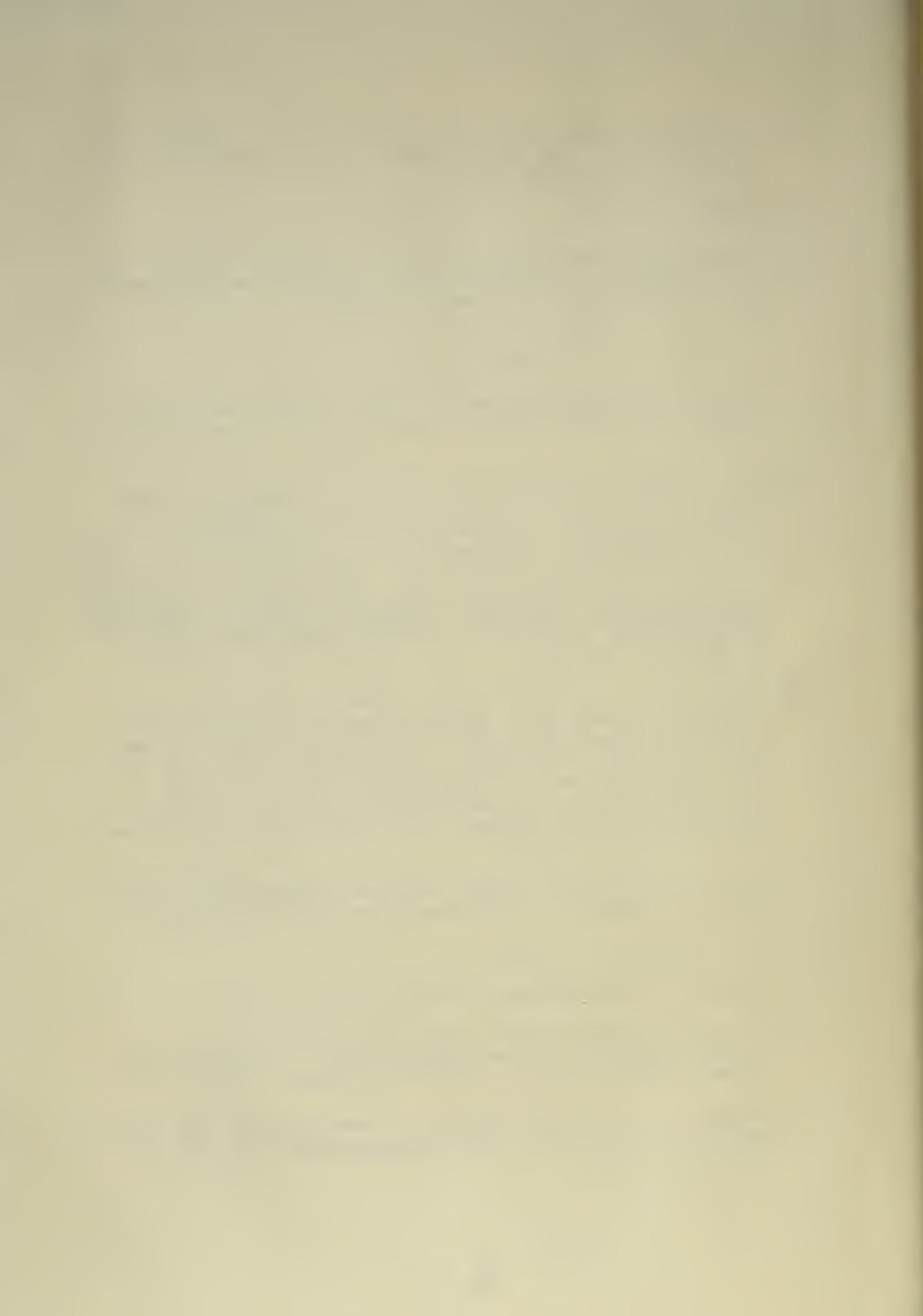
10. The classification "Resistance Transducer" is generally restricted to those that use potentiometers for linear and angular displacement measurements within the transducer. There are other types of transducers that may exhibit a resistive output, e.g., strain-gage transducers and pressure-sensitive intermetallic resin transducers.
11. The carbon strip transducer is one of the Computer Instruments Corporation Series 6000 pressure transducers. Data supplied by manufacturer.
12. This instrument was designed for use in gun blast pressure versus time measurements; its resolution was approximately 2 psi. Sussholz, B., The Taylor Model Basin Diaphragm Blast Gage, Report 508, David Taylor Model Basin, Washington 7, D. C., p 3, December 1943.
13. Information concerning Dynisco transducer: Dynamic Instrument Company, Incorporated, Bulletin 114A, October 1958.
14. This statement assumes an amplification of four times or greater, a requirement easily achieved by an amplifier.
15. Lion, K. S., Instrumentation in Scientific Research - Electrical Input Transducers, McGraw-Hill Book Company, Inc., 1959, pp 74, 105.
16. Equations from Pearls, Thomas A., A New Condenser-Type Pressure Gage, Report 625, David Taylor Model Basin, Washington 7, D. C., pp 37-8, 40.
17. Roark, R. J., Formulas for Stress and Strain, McGraw-Hill Book Company, Inc., 1954, pp 194-5.
18. Pearls, op cit. No-load capacitance computed from Equation (4) therein.
19. Private communication with T. Kite Sharpless of Technitrol Engineering dated September 30, 1960. Data concerns 115H3 stretch diaphragm head.

20. Pearls, op cit, pp 21-2, figs. 7 and 9. Author indicated use of special circuitry which gave this linearity for a short range.
21. ibid, pp 17-9
22. Capacitive reactance (X_c , ohms) varies inversely with the product of capacitance (C , farads) and frequency (f , sec⁻¹) in the following manner:

$$X_c = \frac{1}{2\pi fC}$$

Transducer capacitances are quite small, usually between 10 $\mu\mu\text{f}$ and several hundred $\mu\mu\text{f}$. Lion, op cit, p 70.

23. An increase of frequency decreases capacitive reactances in all parts of the bridge, and raises the bridge unbalance current (hence the system sensitivity). For a discussion concerning the adverse effects of increasing frequency, especially with respect to capacitive leakage see Pender, H. and McIlwain, K., Electrical Engineers' Handbook - Electric Communication and Electronics, Third Ed., John Wiley and Sons, 1936, p 4-35, et passim.
24. Sensitivity increases with operating voltage. The maximum voltage that could be used is the breakdown voltage between the plates of the capacitor at maximum diaphragm deflection. Breakdown voltage of air is 76.2 volts per mil separation. Lion, op cit, p 67 and footnote 1. Radiations increase with voltage thus placing another consideration on the choice of operating voltage.
25. Data on Ultradyne system: Private communication with E. L. Amonette of Ultradyne dated July 29, 1960.
26. Lion, op cit, page 83
27. Schaevitz Engineering, Bulletin AA-1A, 1955, p 17
28. Private communications from T. Kowalski of the Davidson Laboratory to Professor C. R. Nevitt dated 19 May 1960 and to the authors, October 1960.
29. Lipshutz, J., and Aronow, M., "Demodulators for Differential Transformers," Electronics Magazine, June 3, 1960, pp 92,94.



30. Private communication with LTJG Gary Bard of the David Taylor Model Basin, January 1961.
31. Data concerning the OoO SSL LVDT: Schaevitz Engineering, Bulletin AA-2, undated, p 2.
32. Bristol Instrument Company, Bulletin AV2001, undated, p 4.
33. This discussion is intended to demonstrate the criterion for maximum voltage transfer, i.e., a load impedance should be considerably higher than the output impedance of the source. For maximum transmission of power, source output and load input impedances should be equal or nearly so.
34. Robeson, F., Physics, The macmillan Company, New York, 1942, pp 199-200.

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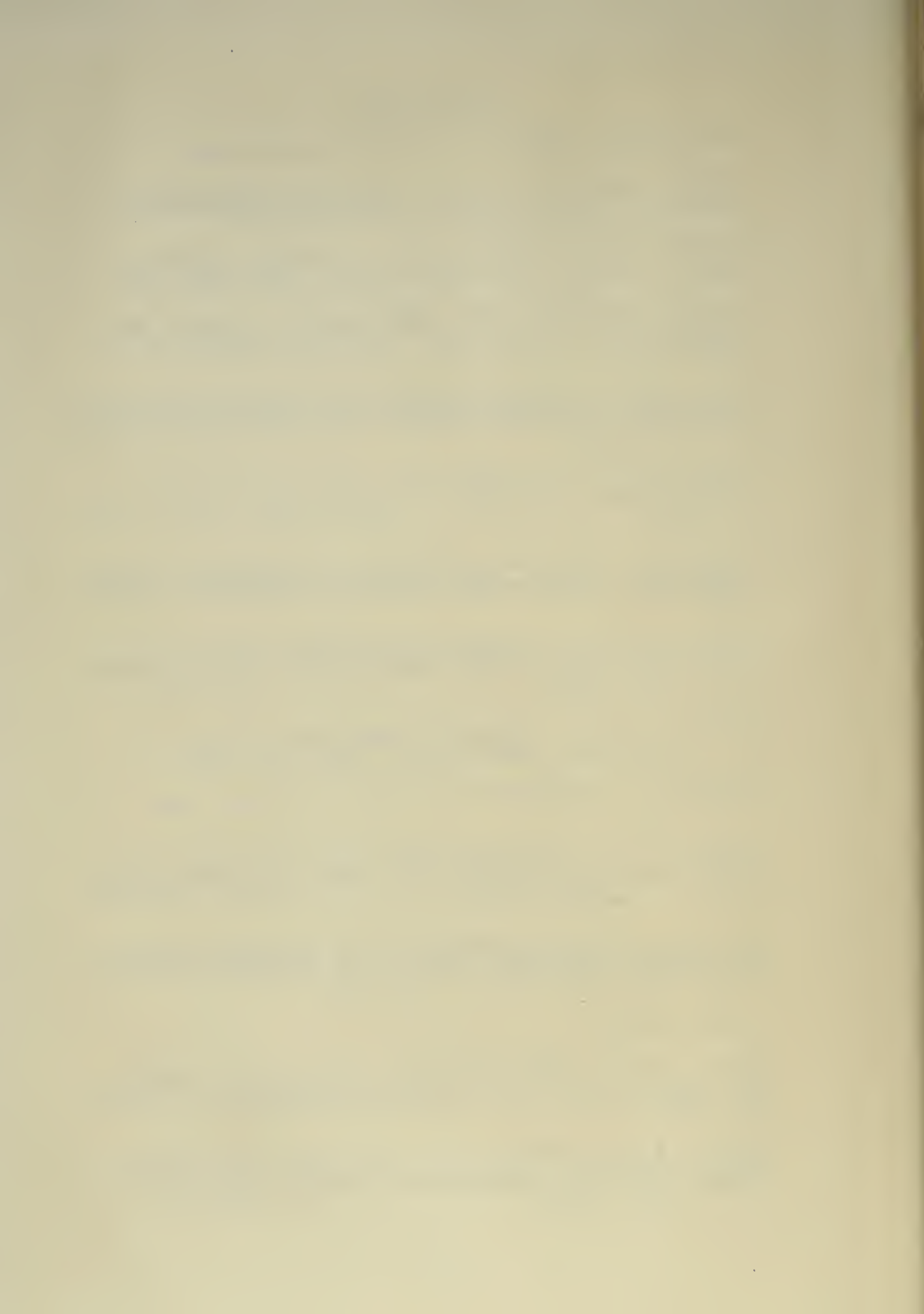
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